EVALUATION OF A GEAR SELECTION AID FOR FUEL EFFICIENT TRACTOR OPERATION

by

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INTRODUCTION

An agricultural tractor for which the available power is not being fully utilized is a source of potential fuel savings (Stephans et al., 1981). Farm tractors are routinely being operated well below their rated power, yet many continue to be operated at rated engine speed or full throttle (Larsen, 1981).

Tractors operating at light loads and full throttle exhibit relatively high specific fuel consumption rates. By utilizing the shift up and throttle back technique, also known as gear up and throttle down, the engine generates more torque at a reduced engine speed for the same ground speed and drawbar pull. With the reduction in parasitic loads, operating at a reduced engine speed typically results in a lower specific fuel consumption. Utilizing the principle has shown fuel consumption reductions as much as 36% (Stephens et al., 1981).

During 1981 a project was begun at Kansas State University to develop a method of making shift up and throttle back recommendations to the tractor operator. The recommendations to the operator would remove the uncertainty of when to shift and which gear to use. The system resulting from this project was called a gear selection aid (Schrock et al., 1982).

Previously an operator had two general 'rules of thumb' to decide when he had shifted up and throttled back too far. First, if the engine rpm dropped more than 6% to 10% when engaging the clutch, the tractor was probably overloaded. The second was if

the tractor did not respond in a reasonable time period when the throttle was pushed forward during field operation, then the engine was overloaded. In both cases the tractor should be shifted down to provide more reserve power, but neither indicated when an operator could shift up.

The shift up and throttle back principle previously had not received full acceptance and use in the fields, probably because of the uncertainties. The operators involved in this research expressed a particular concern for overloading the engine, and causing premature engine failure. The gear selection aid attempted to remove the uncertainties of the shift up and throttle back principle.

The objectives of this research were to revise the models that related gear selection aid inputs to current operating conditions and validate the savings observed during the first test season. Additional objectives were to examine the validity of the values chosen for parameters within the gear selection aid decision algorithm, and how results were affected by changing the parameter values.

The parameter values controlled when or if a shift was recommended by the gear selection aid. The parameter values were selected to stay within the manufacturer's recommended operating limits and the tractor's physical limits. The actual values used within these limits were chosen based on the experience and knowledge of the investigators. A computer simulation program

was developed to examine the validity of the choices. As individual parameters were varied the resulting fuel consumption and frequency of shift were determined by the simulation using field operation data recorded by the gear selection aid.

LITERATURE REVIEW

During recent years several performance monitoring and data acquisition systems for agricultural tractors have been developed using recent advances in electronics and microcomputers (Green et al., 1983). Two performance areas commonly monitored are fuel efficiency and wheel slippage. A few of the systems being developed take action based on the tractor performance, either giving feedback to the operator or directly changing the tractor settings.

Several systems with operator feedback but no recommendation are called efficiency meters or power monitors (Farouault, 1983, Grevis-James, 1980, and Lyne et al., 1980). They indicate to the operator the current operating efficiency. The operator can then select the gear and engine speed combination to obtain a more efficient setting as indicated by the monitor.

The Ecocontrol (Farouault, 1983) is a commercially available tractor efficiency meter. An analog engine tachometer and analog exhaust gas temperature (EGT) gauge are combined into one instrument. The needles are positioned so that they cross over the gauge face. The face of the gauge has been color coded to indicate areas of best fuel economy. When the crossing of the gauge needles is over the green area the tractor is running in a fuel efficient range.

Systems developed to control settings typically position the throttle setting and shift the transmission, often a power shift

transmission, based on the conditions sensed. Chancellor and Thai (1983) reported developing a system with two inputs, the desired speed set by the operator and the drive axle torque. The axle torque determined using strain gauges and a signal amplifier. Based on the inputs a predetermined table selected one of five throttle settings and one of eight transmission gears.

The various systems utilized a variety of sensors to determine current operating conditions. The sensors already mentioned include engine speed, EGT, and drive axle torque. Other systems have used fuel flow meters, ground speed sensors (either by radar or counting wheel revolutions), and draft sensors (such as proving rings with strain gauges) (Morris et al., 1984). Engine speed and injection pump governor control arm position have also been used to determine fuel efficiency (Meiring and Rall, 1979).

As this thesis was being completed, Scott (1984) reported on a gear shift indicator called Economet by Mercedes-Benz. The Economet, which was developed jointly with Bosch for heavy trucks, has several similarities to the gear selection aid. Both systems monitor the engine load, engine speed, and vehicle speed. The Economet monitors throttle position on the truck, the gear selection aid monitors the rack position as set by the tractor governor. In addition, the Economet monitors vehicle mass and clutch movement. Like the gear selection aid, the Economet is programmed with drive train characteristics. Both systems recommend to the operator a potential shift up that will minimize fuel consumption while maintaining vehicle speed. The systems also

use digital displays that show the potential fuel savings using the recommended gear. The Economet will also recommend a down shift on descents to hold the vehicle within a speed limit. The operator has the choice of following the recommendations or not with both systems.

INVESTIGATIONS

Objectives

The objectives of this research were:

1. To change the mathematical models relating the inputs of engine speed and position of the plunger sleeve pin, also referred to as rack position, to fuel consumption and power consumption for the gear selection aid. The revised models to be developed by regression analysis of the data from a PTO dynamometer performance mapping of the engine.

2. To place the tractor in farm situations to verify the fuel savings observed during the first test season.

3. To determine operator acceptance of recommendations made by the gear selection aid and the reliability and accuracy of those recommendations. To also receive operators comments and suggestions for possible changes and improvements.

4. To examine the effect on fuel consumption and frequency of shifting as threshold and parameter values are varied in the gear selection aid decision algorithm. To briefly consider the potential use of alternate algorithms and methods on which to base the decisions for recommending shift up and throttle back settings.

Theory

The shift up and throttle back principle is an attempt to operate the tractor engine at a setting with a lower specific fuel consumption. By shifting up to a higher gear and reducing the engine speed the same ground speed can be maintained. A field tillage operation should require the same work output and time to complete at a constant ground speed. An engine operating at a reduced specific fuel consumption for the same work output will use less fuel to complete the tillage operation.

The specific fuel consumption over most of the operating range of a typical internal combustion engine at a constant power load will decrease as the engine speed decreases and the torque increases. This can be visualized from the generalized engine performance map containing lines of constant specific fuel consumption and constant power in Figure 1.

As an example, a drawbar pull causing 50% of the engine power to be utilized may be operated at any point along the 50% constant power line on the performance map. The point A on Figure 1 represents full throttle, or 100% speed. An alternate setting is to shift the transmission to a higher gear and reduce the engine speed. If the chosen gear results in the forward travel speed remaining constant at the reduced engine speed, the tillage implement draft will also remain constant. The engine power output will remain approximately constant, thus the torque output must increase at the reduced speed. An engine operated at point

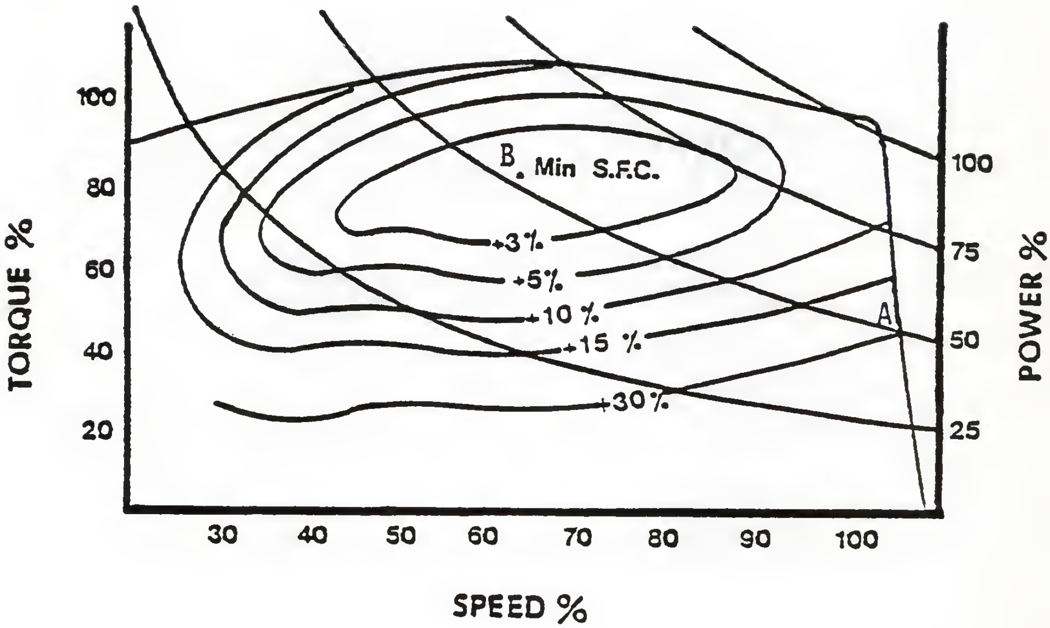

Figure 1. Torque versus speed curve of typical engine with superimposed lines of constant specific fuel consumption and constant power. (Lyne et al., 1980.)

B on the generalized performance map produces the same work, but the specific fuel consumption is approximately 30% lower than point A. The lower specific fuel consumption translates into reduced fuel consumption for a given field operation. The potential savings will vary between tractors because of engine and transmission characteristics, but the concept remains valid for current engines including the one used in this research.

Part of the fuel consumption reduction from shifting up and throttling back results from the reduction in parasitic loads. The parasitic loads such as the cooling fan, hydraulic pump, and alternator will tend to decrease as the rotational speed

decreases. Other gains result from reduced engine friction because of lower piston speed. The PTO performance map for the gear selection aid was developed with all accessories on the engine, but with the air conditioner inoperative. Thus, the savings resulting from reduced loading on the engine during lower speeds were incorporated into the performance map, and into the equations developed from the performance map results.

An analysis of an agricultural operation will generally show that the lowest overall cost results from properly matching the tractor size to the tillage operation. A greatly oversized tractor, even using the shift up and throttle back settings, will usually be less fuel efficient than a smaller tractor that can handle the operation. Considering initial cost and other economic factors, a properly sized tractor will typically produce even larger savings. The concept of shift up and throttle back is applicable to a tractor used in a field operation which applies only light loading compared to its capability. The oversized tractor using the principle can be operated at a reduced fuel consumption rate, thereby improving the economy over operating at full throttle, not over a properly sized tractor.

The shift up and throttle back principle applies best to tractor drawbar loading. PTO (power take off) equipment, when used, normally require a set rotational speed for proper operation. As the PTO shaft is normally a fixed gear ratio from the engine, the engine speed must be set to meet the PTO speed requirement. Normally proper performance of the PTO driven

device takes precedence over any potential savings.

The gear selection aid added a transducer to monitor the plunger sleeve pin position within the American Bosch fuel injection pump used on the IHC model 3588 agricultural tractor. Governor positioning of the plunger sleeve pin, which in turn positions a control sleeve, determines how long the plunger spill port is covered during the pumping stroke of the plunger. This controls the amount of fuel injected to the engine cylinder during a plunger stroke. By attaching a shaft encoder to the plunger sleeve pin its position could be determined. The engine rpm and plunger sleeve pin position, also called rack position though the pump does not use an actual rack, could then be related directly to the fuel consumed per unit time during a PTO performance mapping of the engine. This relationship was used during field operation to calculate an estimated fuel flow.

Engine power could also be determined from the engine rpm and rack position. The rack position is set by the governer based on the current engine speed and the desired engine speed from the throttle linkage. The output power produces torque that reduces the engine speed below the desired setting. The governer continuously positions the rack in an attempt to return the engine to the desired speed. Thus engine speed and rack position determined both fuel consumption rate and power output.

Previous Work

The gear selection aid, as reported by Schrock et al., (1982), uses a Synertek SYM-1 single board computer with a 6502 microprocessor. The system and program were developed and used on an International Harvester model 3588 four-wheel drive tractor. Three inputs from the tractor were provided to the SYM-1; engine speed, transmission output speed, and the digitized position of the fuel pump plunger sleeve pin referred to as rack position. The SYM-1 program related the inputs to current fuel consumption and power using mathematical models developed in a PTO dynamometer performance mapping of the engine. The engine power was recorded in equivalent PTO power for comparison to performance map results. The engine speed and transmission speed were used to determine the current transmission gear ratio.

The SYM-1 program proceeded to check higher transmission gears, the corresponding gear ratios stored in memory, for possible fuel savings. The program assumed that the current ground speed was to be maintained and that the power requirement would therefore remain the same after any shift up. From the transmission output signal the transmission gear ratio was used to determine the engine speed following a shift up. The new engine speed and power were used to estimate the rack position in the new gear. The estimated rack position and new engine speed were then used to estimate the fuel consumption in the higher gear.

The program examined each gear higher than the gear

currently being used while the engine speed and rack position in the higher gear were within specified limits. After finding the optimum gear with minimum fuel consumption, the algorithm checked the difference between fuel consumption in the optimum gear and the next lower gear. Should the next lower gear fuel usage be no more than 0.6 kg/h (0.2 gal/h) above the minimum fuel usage in the optimum gear, the next lower gear was chosen as the optimum gear to use because of its additional torque reserve.

If the optimum gear reduced fuel consumption by more than 1.6 kg/h (0.5 gal/h) from the current operating gear, the SYM-1 provided output for a recommendation to an LED (light emitting diode) display. The display showed the recommended gear and throttle setting, plus the estimated fuel savings per hour. In addition, the current rate of fuel consumption was displayed. The operator had the option to either follow the displayed recommendations or continue with the current settings.

The SYM-1 program also collected data and stored it on cassette tape. Analysis of data saved on tape allowed monitoring operator loading patterns and determining the fuel savings realized from use of the gear selection aid.

The system was placed with farmers during 1982 for field evaluation. During the season much was learned about shortcomings of the current system, but it showed a potential for significant savings. One area of concern in the system was the development of the models relating the three inputs to current

performance. The original model from 1982 was developed from the assumption that the tractor normally operates at power levels above 50% of maximum torque at a given engine speed. Thus the tractor engine performance was mapped from 100% down to 50% torque in 10% increments for engine speeds from 2400 to 1400 rpm, using 200 rpm increments. The 1982 models developed using regression analysis are presented for comparison as equations [1] through [3] in appendix A.

Data from field operation during 1982 showed that the engine regularly operated below 50% of maximum torque at the engine speed being used. Because they were not developed for loading below 50%, the validity of the models was questionable during light loading.

Development of Mathematical Models

The gear selection aid program depends upon the models relating the three tractor inputs to power and fuel consumption, plus a model to estimate the rack position given an engine speed and power output. To develop new equations the engine performance was mapped again prior to the 1983 field evaluation.

The 1983 performance map was developed using an A&W model 400 PTO dynamometer to provide engine loading. At each engine speed and torque combination, after running long enough to stabilize, the torque and fuel consumption were averaged over a 72 second time period. The recorded parameters included the digitized rack position, PTO rotation speed, dynamometer torque, fuel

consumption, and EGT (exhaust gas temperature). All parameters but the EGT were recorded by an ADAC data acquisition system.

The ADAC data acquisition system consisted of a LSI 11/23 processor in a Q-bus back plane and several ADAC boards that interfaced with the Q-bus, along with other necessary accessories such as power supplies and mounting cabinet. An ADAC 1604/OPI optically isolated pulse counter board was used to input frequency signals from two Calex bridge circuits and signals from a magnetic sensor for shaft speed. An ADAC 1664ATTL board for TTL (transistor-transistor logic) inputs read the digital shaft encoder position.

The torque was measured using a strain gauge load cell on the dynamometer. The strain gauges were powered and sensed by a Calex model 166 bridge circuit. The Calex circuit output a frequency proportional to the voltage from the load cell. A pulse counter channel on the ADAC was used to determine the loading, which was converted to PTO torque.

The fuel consumption was determined gravimetrically over the time period, using the slope regression for fuel consumption per unit of time. A fuel bucket, suspended from a strain gauge load cell, was weighed using a Calex circuit and pulse counter channel.

Counting the pulses from a magnetic sensor beside a 60-tooth gear allowed calculation of the PTO rotation speed. This was related to engine speed using the gear ratio between the engine

and the PTO output. The EGT was recorded manually from the digital monitor on the tractor instrument panel.

The encoded rack position refers to the value read from a Litton 76-NB1Ø-2-S-1 1Ø-bit shaft encoder attached to the plunger sleeve pin in the fuel injection pump. The ten parallel lines from the encoder were connected to the ADAC TTL ports. The values ranged from approximately decimal 5Ø at idle without load to approximately 15Ø at full load, with a one unit change representing approximately Ø.352 degree of plunger sleeve pin rotation.

New mathematical models for the SYM-1 were developed by regression analysis from the the second performance map to improve accuracy of calculated values during light loads. The engine performance was mapped for speeds from 24ØØ rpm down to 14ØØ rpm in 2ØØ rpm increments, and from 1ØØ% torque down to 1Ø% torque in 1Ø% increments at each speed. The 1983 models are given as equations [4], [5] and [6] (numbers [4] thru [6] used to prevent confusion with the 1982 model equations in appendix A). Each equation had a good fit statistically, as indicated by Ø.99 or higher r squared values. Extra digits were retained with the model equation constants to minimize calculation errors. The values computed from the equations were accurate to the nearest one tenth (Ø.1).

The earlier section on theory showed that only the rack position and engine speed were required to determine the current

$$KWHAT = -84.1523 + 0.0640580*RPM + 0.2172268*RACK - 0.0000310556*RPM*RPM + 0.0005306494*RPM*RACK \quad [4]$$

"F" statistic = 21,232, r squared = 0.9992

$$FFHAT = -4.3218 + 0.0047590*RPM - 0.0503982*RACK - 0.0000019147*RPM*RPM + 0.0006615262*RACK*RACK + 0.0000768939*RPM*RACK \quad [5]$$

"F" statistic = 11,439, r squared = 0.9988

$$RKHAT = 124.7008 - 0.0827113*RPM + 1.4695318*KWHAT + 0.0000256426*RPM*RPM - 0.0003370157*RPM*KWHAT \quad [6]$$

"F" statistic = 9325, r squared = .9982

where:

KWHAT = predicted PTO power (kW)
RPM = engine speed (rpm)
RACK = encoded rack position
FFHAT = predicted fuel flow (kg/h)
RKHAT = predicted encoded rack position

fuel consumption and power. Equation [4] estimates the power in kilowatts using terms of engine speed, rack position, engine speed squared, and the product of engine speed and rack position. Equation [5] estimates the current fuel consumption in kg/h using the same terms, plus a rack position squared term. During the iteration process used in the gear selection aid decision algorithm, the engine speed in a higher gear can be determined using the transmission output speed and the gear ratio from a look-up table. With the engine speed from the higher gear and the estimated power at current operating conditions, the rack position in the higher gear can be estimated using equation [6]. The estimated rack position can then be used with the engine speed in the higher gear to estimate the fuel consumption in the higher gear using equation [5].

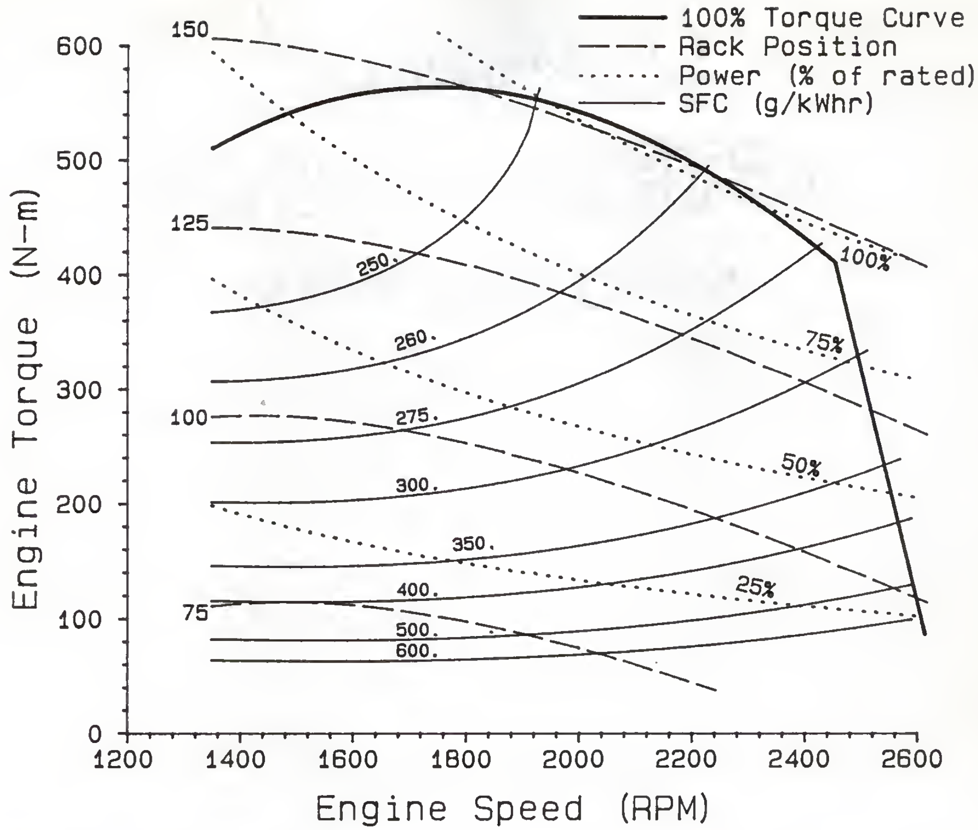

Figure 2. Engine torque versus speed with lines of constant specific fuel consumption and constant rack position for the IHC 3588 engine.

The interaction between engine speed, rack position, fuel consumption, and power are shown in Figure 2. Figure 2 presents a graph of engine torque versus engine speed with lines of constant specific fuel consumption and constant rack positions. The lines of specific fuel consumption and rack position were developed using the mathematical models.

As with the 1982 models, the 1983 models were compared to the Nebraska Tractor Test 1320 results for the IHC model 3588 tractor. The mathematical models used the engine speed and power

Table 1. Comparison of Model Predictions to Nebraska Test 1320.

Nebraska Test 1320			1982 Model		1983 Model	
Power kW	RPM	Fuel Flow kg/h	Predict kg/h	Diff. %	Predict kg/h	Diff. %
112.25	2400	30.37	29.56	-2.7	30.44	0.2
97.95	2468	27.89	27.12	-2.8	27.99	0.3
75.23	2522	23.57	23.46	-0.5	24.03	2.0
51.04	2566	19.33	19.95	3.2	20.09	3.9
25.96	2611	15.02	16.79	11.8	16.38	9.1
0.00	2650	10.41	13.84	33.0	12.82	23.1

reported in the tractor test as input values. The models predicted fuel consumption values almost identical to the test results for the higher loads at full throttle, as can be seen in Table 1. As the load decreased the computer model began overestimating the fuel consumption. The Nebraska tractor test data represent the extreme outer boundary of the data used in developing the mathematical models, thus some discrepancy can be expected in this region.

The constants in the assembly language program for model equations [1] thru [3] were replaced with the constants from equations [4] thru [6]. The assembly language program was recompiled on an Apple II computer, which also uses a 6502 microprocessor. The EPROM (erasable-programmable read only memory) chip was removed from the SYM-1 and erased under ultraviolet light. The EPROM chip was then reprogrammed with the newly assembled version of the program using an EPROM programmer on an Apple II. With the EPROM chip installed in the SYM-1 the gear selection aid was ready to run with the 1983 models.

DISCUSSION

Collection of Data

The SYM-1 recorded data every 15 minutes while the tractor key switch was on. The recorded data included several minutes during non-field operation. Data with ground speeds above 16 kph (9.94 mph) would normally be road travel. Speeds below 3 kph (1.61 mph) would occur either during a gear shift, during travel other than for tillage work, or while the tractor was stopped. A minute of data that had speeds outside the 3 to 16 kph range was rejected by the computer program that summarized data. The lower ground speed limit was increased to 5 kph (3.11 mph) when the data was used for input to the simulation program. Data from operation between 3 and 5 kph upon examination were almost entirely non-field operation.

Occasionally several minutes of data were within the ranges while traveling between fields. Because of the very light loads for these conditions the specific fuel consumption was up to 5 times greater than when working. Changing the ground speed to zero (0) caused these few occurrences to be rejected as invalid data.

Other data were also rejected for various reasons. The 4 second data recorded during a one-half hour period with operator 10 had rack readings that were above the capability of the tractor. The power from the high rack readings was, at times, almost double the maximum of 115.4 kW. Because the problem did not

repeat itself the cause of the erroneous readings could not be determined. Placing an invalid year in the date caused the data to be rejected during analysis.

Three other minutes of data were giving erroneous results. Apparently the operators had removed the load momentarily and immediately re-applied loading. In one case the load dropped to a negative power, possibly from going down hill with the implement momentarily raised out of the ground. The calculated specific fuel consumption was negative, causing the average for the period of operation to be excessively low. In the other occurrences the power became so low that the computed specific fuel consumption became extremely high, again affecting the resulting average. These data points were removed from the summary in manners similar to those already described.

Two other sections of data were also not included in the summary. One operator did not record when he switched implements, and could not remember the date. Thus three days were not included because the implement used was uncertain. One additional day from another operator was not used because the data were exceptionally erratic. The power requirements, ground speed, and engine speed all varied greatly throughout the day. Either the operator was changing settings to watch the display change or was doing very unusual work.

The gear selection aid recorded on cassette tape 15,997 one minute data averages and 38,339 four second data averages that

were considered valid. Of this data from the ten operators, 3668 minute averages were operated with the display switched off and 8788 minutes with the display on for comparison of fuel consumption. The fuel consumption of the remaining data could not be directly compared because the operating conditions changed.

Field Evaluation for 1983

The data from actual field operation are summarized in Tables 2 and 3. Operators 1 through 6 used the tractor during 1982 with the first model. This data have been included for comparison purposes. The use by operators 1 through 4 was discussed by Schrock et al., (1982). Operators 7 through 10 used the tractor with the revised 1983 mathematical models.

The gear selection aid was equipped with a switch to turn off the output display, while still allowing the SYM-1 to record operating data on cassette tape. When the tractor was placed with an operator the display switch was initially turned off so that the normal operator load patterns and tractor settings could be determined. Later the display switch was turned on allowing the display to make recommendations when appropriate. This arrangement made it possible to compare the load and operator settings of the tractor with and without the use of the display. In Tables 2 and 3, the 'a' suffix indicates the display was turned off. A 'b' suffix indicates the display was on and capable of making shift up and throttle back recommendations.

TABLE 2A. Daily Summary of 1982 Field Data

III GEAR SELECTION AID PROJECT DAILY DATA AND LOAD HISTORY

DATE	LOCATION	OPERATION	ENGINE rpm	SPEED km/h	POWER kW	SFC g/kWh	MEP kPa	LOAD HISTORY, PERCENT TIME AT INDICATED PERCENT POWER LEVEL 0+	10+	20+	30+	40+	50+	60+	70+	80+	90+	MINUTES
9/20/82	1	NH3 appl.	1935	9.41	77.5	262.	631.	0	1	1	1	4	12	34	43	4	0	76
9/21/82	1	NH3 appl.	2145	9.40	79.9	273.	588.	0	0	0	0	1	9	44	38	8	0	38
9/22/82	1	NH3 appl.	1951	9.50	80.0	263.	546.	0	0	0	0	1	7	44	44	4	0	95
9/24/82	2	6.5m Drill	2587	8.55	32.9	498.	200.	0	9	49	39	2	1	0	0	0	0	19
9/25/82	2	6.5m Drill	2582	8.20	32.1	521.	195.	2	11	46	35	5	1	0	0	0	0	24
9/27/82	2	6.5m Drill	1876	8.78	37.5	352.	318.	1	4	23	67	6	0	0	0	0	0	39
9/28/82	2	6.5m Drill	1746	8.49	36.0	330.	328.	0	4	31	63	2	0	0	0	0	0	78
9/29/82	2	6.5m Drill	1659	8.31	39.6	300.	376.	0	0	10	85	5	0	0	0	0	0	83
9/30/82	2	4.9m Disk	2030	8.74	55.2	325.	390.	0	0	9	18	30	26	14	4	0	0	7
10/4/82	3	8.1m Drill	1752	8.77	29.3	370.	263.	0	13	68	19	0	0	0	0	0	0	52
10/5/82	3	8.1m Drill	1702	8.53	30.2	352.	279.	0	8	77	15	0	0	0	0	0	0	67
10/6/82	3	8.1m Drill	1715	9.72	30.5	355.	281.	0	10	69	20	1	0	0	0	0	0	53
10/7/82	3	9.1m Drill	1731	8.71	30.0	371.	273.	2	10	65	22	1	0	0	0	0	0	55
10/9/82	3	8.1m Drill	1646	8.24	35.1	317.	336.	0	0	48	49	3	0	0	0	0	0	22
10/10/82	2	8.1m Drill	1796	8.50	34.2	331.	319.	0	2	58	33	8	0	0	0	0	0	11
10/10/82	3	8.1m Drill	1669	8.36	31.5	341.	297.	0	7	56	37	0	0	0	0	0	0	5
10/11/82	3	8.1m Drill	1682	8.42	34.1	325.	321.	0	1	54	46	0	0	0	0	0	0	21
10/12/82	3	8.1m Drill	1573	7.88	32.4	323.	324.	0	6	60	33	1	0	0	0	0	0	75
11/17/82	4	5.5m Chisel	2379	7.47	94.0	285.	631.	0	0	0	4	4	7	13	8	18	47	7
11/18/82	4	5.5m Chisel	2027	7.99	79.7	275.	619.	0	1	1	7	5	14	19	26	16	11	39
11/19/82	4	5.5m Chisel	1956	7.38	74.3	282.	593.	1	3	1	3	10	26	19	14	13	10	46
11/20/82	4	5.5m Chisel	1870	7.77	62.5	286.	521.	0	4	3	16	18	19	18	15	5	1	70
11/22/82	4	5.5m Chisel	1701	5.09	42.6	303.	397.	0	1	21	47	21	9	1	0	0	0	11
11/26/82	4	5.5m Chisel	1902	6.22	46.3	303.	385.	2	2	11	37	29	16	3	1	0	0	47
11/27/82	4	5.5m Chisel	2014	6.66	43.6	330.	342.	0	1	10	49	38	3	0	0	0	0	9

TABLE 2B. Daily Summary of 1983 Field Data

DATE	LOC	OPERATION	ENGINE rpm	SPEED Km/h	POWER kW	SFC g/kWh	MEP kPa	LOAD HISTORY, % TIME IN PERCENT POWER LEVEL 0+	10+	20+	30+	40+	50+	60+	70+	80+	90+	100+	MINUTES
12/22/82	5b	8.2m Disk	2440.	8.13	97.2	287.	422.	0.	0.	4.	1.	0.	0.	1.	4.	45.	25.	0.	26.
12/24/82	5b	4.6m Chisel	2454.	8.10	97.3	289.	425.	1.	1.	0.	1.	0.	0.	3.	19.	40.	34.	0.	23.
1/12/83	6a	9.1m Disk	2261.	8.46	50.9	341.	355.	0.	1.	6.	35.	28.	25.	4.	1.	1.	0.	0.	13.
1/13/83	6a	9.1m Disk	2083.	8.88	67.9	293.	513.	0.	2.	5.	6.	7.	24.	33.	19.	2.	0.	0.	25.
1/14/83	6a	9.1m Disk	1986.	8.50	61.2	284.	485.	0.	0.	2.	7.	31.	35.	23.	2.	0.	0.	0.	13.
1/15/83	6a	9.1m Disk	2142.	9.25	65.6	289.	477.	0.	0.	6.	5.	25.	22.	25.	18.	1.	0.	0.	34.
1/15/83	6b	9.1m Disk	1938.	9.56	47.2	275.	543.	0.	0.	1.	4.	6.	46.	39.	5.	0.	0.	0.	13.
1/17/83	6b	9.1m Disk	1800.	8.93	57.7	776.	507.	0.	0.	4.	4.	41.	45.	6.	0.	0.	0.	0.	17.
1/18/83	6b	9.1m Disk	1867.	9.75	57.7	286.	485.	0.	4.	4.	4.	23.	38.	7.	1.	0.	0.	0.	13.
7/25/83	7a	6.1Dsk/SprTth	2051.	8.04	64.3	282.	492.	0.	0.	1.	2.	13.	60.	24.	0.	0.	0.	0.	51.
7/25/83	7b	6.1Dsk/SprTth	2096.	8.32	69.5	283.	524.	0.	0.	2.	1.	4.	33.	53.	7.	0.	0.	0.	41.
7/28/83	8a	6.7m Disk	2524.	9.31	59.0	373.	369.	0.	1.	5.	27.	8.	26.	25.	7.	0.	0.	0.	21.
7/28/83	8b	6.7m Disk	1914.	9.58	65.5	248.	539.	0.	0.	0.	2.	5.	67.	26.	0.	0.	0.	0.	29.
7/29/83	8b	6.7m Disk	1977.	9.64	62.3	290.	503.	0.	1.	0.	8.	6.	49.	14.	1.	0.	0.	0.	19.
7/30/83	8b	6.7m Disk	1836.	7.98	43.3	362.	366.	2.	2.	11.	43.	29.	12.	0.	0.	0.	0.	0.	43.
8/ 1/83	8b	6.7m Disk	1832.	8.74	46.4	257.	403.	1.	3.	8.	23.	57.	8.	0.	0.	0.	0.	0.	16.
8/ 3/83	7a	Drag/Harrow	1702.	8.50	43.3	283.	405.	0.	0.	4.	60.	36.	0.	0.	0.	0.	0.	0.	55.
8/ 4/83	7a	Drag/Harrow	1837.	9.20	50.9	261.	437.	0.	0.	0.	6.	89.	5.	0.	0.	0.	0.	0.	83.
8/ 5/83	7a	Drag/Harrow	1979.	9.91	50.5	295.	401.	0.	0.	0.	3.	93.	3.	0.	0.	0.	0.	0.	2.
8/ 5/83	7b	Drag/Harrow	1948.	9.89	52.4	293.	428.	0.	0.	0.	9.	79.	12.	0.	0.	0.	0.	0.	115.
8/ 6/83	7b	Drag/Harrow	2001.	9.90	48.2	306.	380.	0.	0.	0.	37.	60.	3.	0.	0.	0.	0.	0.	71.
8/ 8/83	7b	Drag/Harrow	2104.	10.54	54.2	304.	405.	0.	0.	0.	2.	82.	15.	1.	0.	0.	0.	0.	110.
8/12/83	9a	5.5m Disk	2031.	7.81	60.8	303.	472.	1.	3.	2.	3.	17.	55.	18.	1.	0.	0.	0.	36.
8/13/83	9a	5.5m Disk	1732.	8.61	67.1	265.	613.	0.	1.	3.	5.	6.	30.	53.	2.	0.	0.	0.	62.
8/15/83	9a	5.5m Disk	2037.	7.94	65.7	283.	509.	0.	0.	3.	5.	6.	43.	43.	1.	0.	0.	0.	30.
8/15/83	9b	5.5m Disk	1615.	7.88	49.7	273.	487.	0.	2.	7.	13.	62.	16.	0.	0.	0.	0.	0.	14.
8/17/83	9b	5.5m Disk	1507.	7.47	45.4	292.	478.	1.	1.	5.	47.	45.	2.	0.	0.	0.	0.	0.	16.
8/18/83	9b	5.5m Disk	1659.	8.07	72.0	251.	483.	0.	0.	0.	1.	10.	24.	46.	20.	0.	0.	0.	74.
8/22/83	9b	5.5m Disk	1724.	8.55	68.0	264.	627.	0.	2.	3.	3.	3.	27.	60.	3.	0.	0.	0.	53.
8/23/83	9b	5.5m Disk	1841.	8.64	77.8	265.	663.	1.	2.	1.	2.	8.	17.	23.	24.	9.	12.	0.	47.
8/24/83	9b	5.5m Disk	1806.	8.41	70.0	271.	611.	1.	3.	3.	2.	4.	19.	39.	23.	3.	1.	0.	35.
8/24/83	9b	9.8m F.Cultiv	1822.	8.82	77.4	255.	471.	0.	0.	0.	0.	2.	27.	30.	40.	2.	0.	0.	7.
8/25/83	9b	9.8m F.Cultiv	1713.	8.44	63.5	265.	581.	1.	1.	1.	4.	17.	40.	30.	5.	0.	0.	0.	46.
8/26/83	9b	9.8m F.Cultiv	2022.	10.12	91.7	259.	713.	0.	1.	0.	0.	1.	1.	9.	62.	33.	16.	0.	19.
8/31/83	9b	5.5m Disk	1835.	8.90	79.6	256.	684.	0.	0.	2.	6.	3.	9.	24.	50.	9.	0.	0.	62.
9/ 1/83	9b	5.5m Disk	1815.	8.41	71.5	261.	621.	0.	0.	2.	2.	7.	33.	30.	22.	4.	0.	0.	56.
9/ 2/83	9b	5.5m Disk	1764.	8.71	61.8	265.	551.	0.	0.	1.	2.	43.	28.	18.	6.	2.	1.	0.	37.
9/ 3/83	9b	5.5m Disk	1771.	7.95	55.3	275.	491.	0.	1.	3.	16.	39.	31.	8.	1.	0.	1.	0.	37.
9/ 7/83	9b	5.5m Disk	1709.	7.31	48.6	277.	448.	0.	1.	4.	18.	76.	0.	1.	0.	0.	0.	0.	12.
9/ 9/83	10a	6.1m Disk	2412.	9.02	82.4	317.	535.	1.	3.	3.	3.	4.	6.	15.	27.	27.	12.	0.	29.
9/12/83	10a	6.1m Disk	2411.	10.94	91.1	321.	598.	0.	0.	2.	3.	3.	5.	17.	19.	8.	44.	0.	71.
9/13/83	10a	6.1m Disk	2442.	9.85	87.3	311.	565.	0.	2.	3.	2.	2.	3.	14.	30.	17.	26.	0.	63.
9/14/83	10a	6.1m Disk	2436.	9.13	89.4	307.	582.	0.	1.	3.	3.	3.	1.	7.	37.	21.	24.	0.	26.
9/14/83	10b	6.1m Disk	2286.	10.48	94.5	289.	657.	0.	1.	2.	2.	2.	3.	5.	16.	24.	44.	0.	59.
9/15/83	10b	8.7m F.Cultiv	2029.	9.43	83.8	270.	659.	0.	0.	2.	4.	3.	3.	10.	52.	22.	6.	0.	20.
9/17/83	10b	8.7m F.Cultiv	2436.	9.57	87.3	328.	561.	1.	2.	2.	1.	3.	3.	5.	33.	39.	11.	0.	41.
9/21/83	10b	8.7m F.Cultiv	2377.	9.16	97.0	293.	648.	0.	0.	2.	6.	2.	3.	3.	8.	21.	55.	0.	13.
9/22/83	10b	8.7m F.Cultiv	2399.	9.70	84.3	307.	548.	1.	3.	2.	2.	4.	7.	13.	31.	18.	19.	0.	52.
9/23/83	10b	8.7m F.Cultiv	2342.	9.03	77.7	313.	512.	1.	7.	4.	2.	3.	7.	25.	18.	16.	18.	0.	20.
9/23/83	10b	6.1m Disk	2353.	8.26	99.1	284.	660.	0.	0.	3.	3.	1.	0.	3.	10.	21.	58.	0.	23.
9/24/83	10b	6.1m Disk	2345.	7.88	85.4	314.	564.	1.	8.	3.	5.	1.	3.	2.	16.	34.	27.	0.	13.
9/26/83	10b	6.1m Disk	2382.	8.69	93.9	300.	622.	0.	1.	4.	4.	3.	3.	4.	8.	23.	50.	0.	28.
9/26/83	10b	8.7m F.Cultiv	2395.	9.43	87.2	297.	569.	0.	2.	2.	2.	2.	3.	3.	39.	30.	13.	0.	30.
9/27/83	10b	8.7m F.Cultiv	2367.	9.39	95.3	286.	633.	0.	0.	1.	1.	4.	4.	7.	18.	19.	65.	0.	34.
9/28/83	10b	8.7m F.Cultiv	2379.	10.31	92.2	295.	612.	0.	0.	4.	1.	4.	7.	12.	12.	17.	44.	0.	30.
9/29/83	10b	8.7m F.Cultiv	2358.	9.30	102.8	279.	690.	0.	0.	0.	1.	0.	2.	6.	8.	17.	66.	0.	52.
9/30/83	10b	8.7m F.Cultiv	2366.	9.38	93.5	295.	614.	1.	1.	3.	1.	1.	2.	1.	19.	44.	27.	0.	23.
10/ 1/83	10b	8.7m F.Cultiv	2333.	9.07	103.7	275.	704.	0.	0.	0.	0.	1.	0.	2.	17.	22.	62.	0.	30.
10/15/83	10b	6.1m Disk	2429.	10.56	92.7	297.	604.	0.	1.	2.	1.	1.	1.	7.	39.	16.	32.	0.	52.
10/17/83	10b	6.1m Disk	2341.	9.51	73.1	327.	481.	4.	2.	2.	2.	5.	9.	36.	29.	7.	3.	0.	33.
10/18/83	10b	6.1m Disk	1796.	8.04	64.6	223.	569.	1.	2.	4.	2.	11.	43.	22.	12.	2.	1.	0.	11.

TABLE 3. Load History of Ten Operators

DATE	LOC	OPERATION	ENGINE rpm	SPEED km/h	POWER kW	SFC g/kWh	MEP kPa	LOAD HISTORY, % TIME IN PERCENT POWER LEVEL 0+	10+	20+	30+	40+	50+	60+	70+	80+	90+	100+	MINUTES
9/82	1a	6.5m Drill	2584.	8.40	32.5	511.	198.	1	10	47	37	4	1	0	0	0	0	0	43
9/82	1b	6.5m Drill	1739.	8.47	37.8	322.	346.	0	2	21	73	4	0	0	0	0	0	0	200
10/82	2a	8.1m Drill	1724.	8.43	29.8	360.	272.	0	10	73	16	0	0	0	0	0	0	0	119
10/82	2b	8.1m Drill	1664.	8.39	31.9	341.	304.	0	6	61	31	1	0	0	0	0	0	0	257
9/82	3b	NH3 appl.	1930.	9.50	79.1	264.	630.	0	0	0	1	2	9	41	42	5	0	0	209
11/82	4b	5.5m Chisel	1938.	7.25	63.4	292.	512.	1	2	5	18	17	17	14	12	7	6	0	231
12/82	5b	8.2m disk	2460.	8.13	97.2	287.	622.	0.	0.	4.	1.	0.	0.	1.	4.	63.	23.	0.	26.
12/82	5b	4.6m Chisel	2454.	8.10	97.3	289.	625.	1.	1.	0.	1.	0.	0.	3.	19.	40.	34.	0.	23.
1/83	6a	9.1m Disk	2127.	8.94	63.4	298.	470.	0.	1.	4.	10.	21.	25.	24.	13.	1.	0.	0.	85.
1/83	6b	9.1m Disk	1868.	9.22	60.6	279.	511.	0.	1.	3.	4.	25.	49.	16.	2.	0.	0.	0.	43.
7/83	7a	6.1Dsk/SprTth	2051.	8.04	44.3	282.	492.	0.	0.	1.	2.	13.	60.	24.	0.	0.	0.	0.	51.
7/83	7b	6.1Dsk/SprTth	2096.	8.32	69.5	283.	524.	0.	0.	2.	1.	4.	33.	53.	7.	0.	0.	0.	41.
8/83	7a	Drag/Harrow	1786.	8.93	48.1	282.	424.	0.	0.	1.	27.	68.	3.	0.	0.	0.	0.	0.	140.
8/83	7b	Drag/Harrow	2019.	10.13	52.0	300.	408.	0.	0.	0.	13.	76.	11.	0.	0.	0.	0.	0.	296.
7/83	8a	6.7m Disk	2524.	9.31	59.0	373.	369.	0.	1.	3.	27.	8.	26.	23.	7.	0.	0.	0.	21.
7/83	8b	6.7m Disk	1939.	9.61	64.2	277.	524.	0.	1.	0.	4.	5.	68.	21.	0.	0.	0.	0.	48.
7/83	8blo	6.7m Disk	1871.	8.19	44.1	334.	376.	2.	2.	11.	38.	36.	11.	0.	0.	0.	0.	0.	59.
8/83	9a	5.5m Disk	1916.	8.16	64.6	283.	537.	0.	2.	2.	4.	9.	42.	35.	1.	0.	0.	0.	108.
9/83	9b	5.5m Disk	1741.	8.38	69.3	260.	629.	0.	1.	2.	2.	12.	26.	40.	13.	1.	0.	0.	257.
9/83	9blo	5.5m Disk	1692.	7.73	50.5	314.	473.	1.	1.	5.	22.	49.	17.	4.	0.	0.	0.	0.	81.
9/83	9bhi	5.5m Disk	1838.	8.79	78.8	260.	675.	0.	1.	1.	3.	5.	13.	24.	39.	9.	3.	0.	109.
8/83	9b	9.8m F.Cultv	1805.	8.92	72.3	263.	624.	1.	1.	1.	3.	11.	28.	25.	18.	9.	4.	0.	72.
9/83	10a	6.1m Disk	2425.	10.03	88.3	315.	575.	0.	1.	3.	3.	3.	4.	14.	26.	16.	30.	0.	189.
9/83	10b	6.1m Disk	2327.	9.61	89.2	296.	604.	1.	2.	2.	2.	3.	5.	10.	22.	19.	34.	0.	219.
9/83	10b	9.8m F.C.NH3	2349.	9.49	85.3	307.	571.	1.	2.	2.	2.	3.	5.	11.	31.	24.	18.	0.	146.
9/83	10b	9.8m F.Cultv	2366.	9.46	96.6	287.	644.	0.	0.	2.	1.	2.	3.	6.	17.	23.	46.	0.	199.

Operator 7 began using the tractor in late July, 1983, to pull a 6.1 m disk and spring tooth combination. The spring tooth was pulled behind the disk to smooth the ground. The display was off for about 3 1/2 hours. After turning the display on, the first display recommendation and its significance were described to the operator. He showed only a slight interest, and continued to operate in the same gear. The operator, a hired hand of high school age, choose to ignore the recommended settings. Although he was already running in a shift up and throttle back manner, the tractor could have been geared up further for additional savings.

The tractor was used briefly by another operator while operator 7 did some non-field work. When the tractor was returned, it was used to pull a drag in front of a spike tooth harrow. The "drag" was an old truck frame used to level and smooth the seedbed before planting alfalfa under a center pivot irrigation system. At the tractor settings being used the potential savings were less than the threshold of 1.6 kg/h, so the gear selection aid could not make a recommendation. The gear selection aid provided no benefits for operator 7. The operator was already using shift up and throttle back settings and, when a change was recommended, he did not follow display recommendations.

Operator 8 represents an individual that could benefit the most from a gear selection aid. The tractor was used to pull a 6.7 m disk. With the display off, the tractor was operated at

approximately 9 1/2 kph ground speed and the engine at full throttle, about 2525 rpm. When the display was turned on, the operator began following the display recommendations. The ground speed and power remained approximately the same, but the engine was throttled back to approximately 1940 rpm by shifting up. In the same field the operator reduced fuel consumption from 373 g/kW·h to 277 g/kW·h, a 25.7% reduction. The operator continued using the tractor in another field where the loading was considerably lighter. A separate summary was entered in Table 3 under 8blo, for operator 8 with display off and low loads. The display was off during part of the data included under 8blo, but the operator continued to use the shift up and throttle back setting. So all the data from the second field were placed under 8blo.

Operator 9 used the tractor mostly for disking previously tilled wheat stubble ground. The tractor was operated for three days with the display off. During that time it was operated in a shift up and throttle back manner with engine speed around 1900 to 1950 rpm. After turning the display on, the operator generally followed the display recommendations. The daily summary of disking showed a wide variation in loading. For comparison data within 15% of the power requirements when the display was off was summarized together. Comparison of the fuel economy showed a 8.1% improvement with the display on. The gear selection aid provided additional savings over the settings already being used. The remaining data for disking were summarized as lower loading and higher loading.

The tractor was operated by both a father and his son at location 9. Because they did not record who was operating, the data was combined under one operator. During one visit the father commented that he had trouble looking up at the right time to see the display. Occasionally he would look in time to see the display go off, but was unable to read the display. At least one period of data showed that recommendations were being made on a regular basis, but not being followed. This data was included under the 8b summary. Had it been excluded, the savings attributed to the gear selection aid would have been greater.

The extremely dry 1983 summer resulted in the tractor being left with operator 9 longer than planned. During mid-August the dry weather had stopped almost all field work in Kansas. With rains in the latter part of August this operator was able to use the tractor further. Some of the fluctuation in power consumption by the disk can probably be attributed to changes in soil moisture. The operator briefly used the tractor to pull a 9.8 m field cultivator, but a comparison with and without the gear selection aid was not made.

Operator 10 loaded the tractor more heavily than any other operator during 1983. Examination of the data showed several of the four second data recordings were at the 100% power level for the entire minute.

Initially the display was off during 3 1/2 days of disking. With the display on the operator stated that recommendations were

being made, but following the recommendations reduced the tractor lugging ability. The SYM-1 program algorithm was written to not recommend a gear if loading exceeded 95% of engine torque. A possible problem developed in using a constant rack position value as the criteria to determine overload, which will be discussed later.

The high loads resulted in operator 10 receiving only a 6% savings in fuel. However, effective use of the aid can be observed in the Table 2B daily summary on October 18, 1983. The power requirement dropped considerably that day, and the tabulation shows the operator did shift up and throttle back. The operator was using the gear selection aid to full advantage for this light loading.

The tractor was also used by operator 10 to pull a 9.8 m field cultivator. The field cultivator was attached at two different times. Initially, it was used to incorporate anhydrous ammonia (NH3) while pulling a nurse tank. The second time the same field cultivator was used for field tillage. The two uses are kept separate in the summary of field operation.

The summary of fuel savings for the 1983 season indicates smaller benefits than the previous year. During 1983 one operator ignored the display, but he and one other operator were already using shift up and throttle back settings. Another operator had high load patterns resulting in minimal fuel savings. Only one operator had large fuel savings attributed to the

gear selection aid. The operator fuel savings attributed to the gear selection aid ranged from no savings up to 25.7% during 1983. For operators 7 through 10 the average fuel savings was approximately 9.9%. This is considerably lower than the 19.8% fuel savings for operator 1 through 4.

The load histories in Tables 2 and 3 showed a considerable variation in loading, even within the same day. As an example, in Table 2A on September 23, 1983, the loading on the tractor had a relatively even distribution from 50% to 100% of rated power. While variation was expected, the large variation within the same day and same operation was not.

The changes in loading determine which gear is fuel efficient, yet provides adequate reserve power. For example, operator 9 noted that in a large field the recommendation for a long, gentle downward slope was inadequate for traveling up the slope. The gear selection aid was still beneficial in deciding which gear to use for the upward slope. But the operator chose to remain in the same gear for the down slope travel.

Gear Selection Aid Performance Evaluation

Acceptance of the gear selection aid by operators varied from neutral to very receptive. The system offered advice in a generally passive manner, therefore it did not become a source of annoyance if the advice was not followed. A regular comment from operators was that the system could be more active.

The logic used in the SYM-1 was to display a recommendation for one minute if the threshold fuel savings of 1.6 kg/h (0.5 gal/h) was met, then clear the entire display one minute. When the threshold was not met the output display remained cleared. Thus, the operator was not quite sure the device was functioning properly when it was not making recommendations. Displaying the fuel flow on a continuous basis with regular updates would alleviate this last problem, plus provide beneficial information to the operator. The remaining outputs to the display (fuel savings, gear and throttle settings) could be updated each minute while a shift recommendation can be made. This approach would help the operators that reported missing display recommendations.

The gear selection aid performed reliably during most of the field evaluation. A few problems occurred early, such as electrical noise interference and shaft encoder problems. Once these problems were eliminated the system operated almost trouble free.

Only operator 10, who loaded the tractor very heavily, reported that the computer had recommended a setting which produced insufficient torque reserve. Reviewing the performance map data and program logic provided an explanation for the inappropriate recommendations. The program attempted to prevent engine overloading by recommending a gear shift only if the estimated rack position was below 140, regardless of the engine speed.

From 2400 to 1700 rpm the rack setting increases for effec-

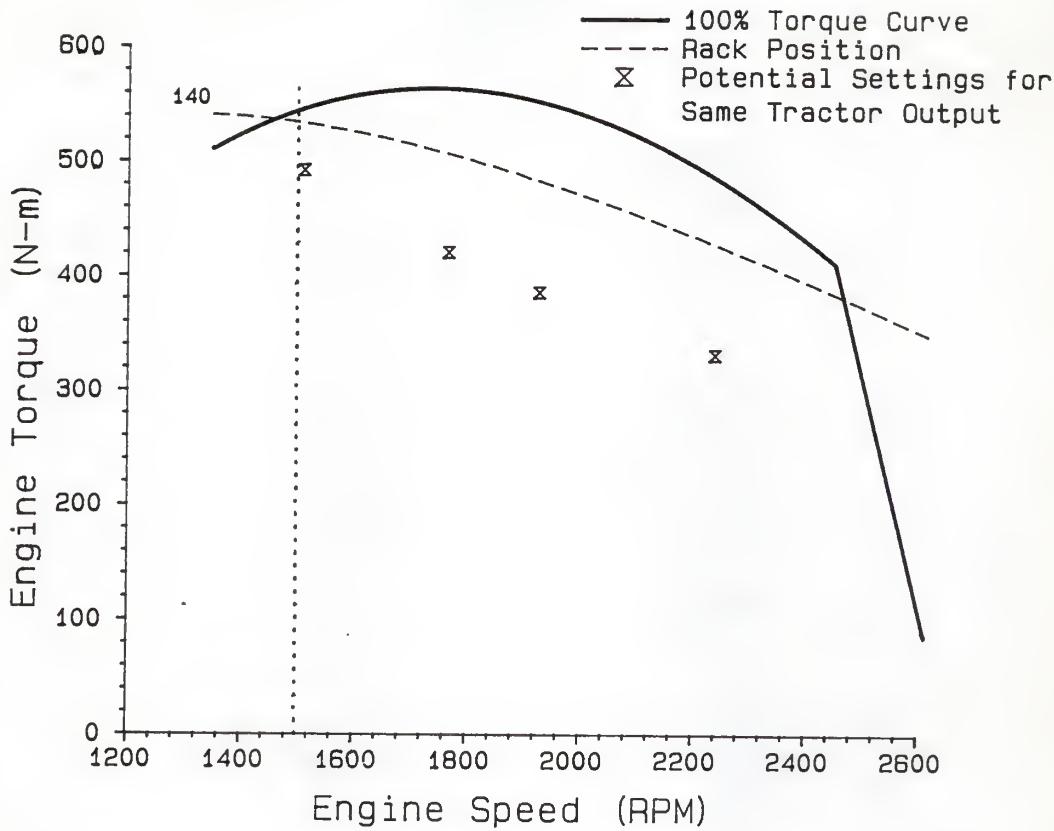

Figure 3. Engine torque versus speed with rack limit and engine speed limit in gear selection aid and potential engine operating points for conditions used by operator 10.

tive torque rise as the engine speed decreases. At speeds below 1700 rpm, the governer reduces maximum rack setting as speed decreases. Figure 3 shows the maximum torque decreasing as the engine speed decreases toward the 1500 rpm lower limit, while the constant rack position at 140 increases gradually. As the engine speed approached the 1500 rpm lower speed limit and the estimated rack was just below the 140 maximum rack limit, it was possible for the SYM-1 to make setting recommendations that were very near the 100% torque curve. An example of potential settings for

actual data from operator 10 was included on Figure 3 for illustration. Thus the "95% of maximum rack" limit as implemented originally to avoid overloading resulted in insufficient torque reserve at low rpm and loads around 75% of rated power.

For the simulation program a regression equation was developed from the performance map data to estimate the maximum rack at a given engine speed. Incorporating the equation into the decision algorithm would add slightly to the computational load of the microcomputer, but should avoid the problem pointed out here.

The savings attributed to the gear selection aid for each location is summarized in Table 4. The savings ranged from no

Table 4. Summary of Fuel Consumption With and Without Display.

Location	SFC W/O Display g/kW·h	SFC W/Display g/kW·h	% Savings
1	511.	322.	37.0
2	360.	341	0.0[1]
3	311.[2]	264.	15.1
4	401.[2]	292.	27.2
5	----	288.	0.0[3]
6	298.	279.	6.4
7	282.	283.	0.0[4]
8	373.	277.	25.7
9	283.	260.	8.1[5]
10	315.	296.	6.0
		Ave. Savings =	12.5%

1 Savings not attributed to computer.
2 Projected value from Schrock et al. (1982).
3 No savings due to heavy loading.
4 Recommendations were not followed.
5 Additional savings, operator voluntarily used shift up-throttle back settings without display.

savings to a high of 37% savings in fuel by using the gear selection aid. The average for the ten operators was 12.5% fuel savings with the gear selection aid.

Alternate Methods of Sensing Load

The potential of EGT being used to replace the rack for fuel flow and load indication, as used by Renault's Ecocontrol, deserved further consideration. The performance map data was examined for feasibility of using EGT as an indicator of fuel consumption.

The EGT had a correlation of -0.7664 to brake specific fuel consumption, indicating a negative relationship between them. Several regressions were made to construct an accurate model relating EGT, engine speed, and specific fuel consumption. An equation using rpm and EGT only had a r square value of 0.6798 and an "F" statistic of 75.35. Adding the product rpm*EGT in the equation as an independent variable yielded an equation with an r square value 0.6991 and "F" statistic 54.21. A better curve fit was found using rpm, EGT, rpm squared, EGT squared, and rpm*EGT. The resulting regression equation had an r square value of 0.9331 and a "F" statistic of 189.76.

The statistical analysis indicates the rack signal was a more accurate indicator of fuel flow and load sensing. Variations in the ambient air temperature that cause changes in the EGT could also result in a less reliable power and fuel consumption prediction. However, the EGT showed reasonable accuracy in

this brief analysis, and might possibly improve with better resolution. The EGT data used in this analysis was recorded manually from the stock EGT gauge on the tractor, which read in 10° F or 5.6° C increments. The EGT range during the performance map was form 226.7° C (440° F) to 632.2° C (1170° F). Use of the EGT deserves further investigation, since it may simplify and reduce the cost of an effective gear selection aid system.

Simulation of Gear Selection Decision Algorithm

The parameters used in the gear selection aid decision algorithm were chosen based on the experience of the investigators. The tractor manufacturer's recommended operating limits were considered in determining parameter settings. The manufacturer recommended operating the tractor above 1200 rpm and with the EGT below 760° C (1400° F) for acceptable engine durability. The highest EGT recorded during PTO dynamometer testing was 632.2° C (1170° F), well below the stated limit. Because of this difference and the tractor having a warning system for high EGT on the instrument panel, the EGT limit was considered adequately monitored and was not used as a limit in the gear selection aid algorithm.

The low engine speed limit actually used in the decision algorithm was 1500 rpm. Choosing 1500 rpm allowed a safety margin above the recommended minimum operating speed. Also, at 1500 rpm the maximum torque was decreasing as engine speed decreased, with the torque curve peak around 1800 rpm. The 1500 rpm lower

limit reduced the possibility of the engine pulling down and reaching 1200 rpm because of a lack of torque reserve. An additional consideration was that the minimum fuel consumption during the PTO performance mapping was observed around 1600 rpm. Though these considerations were taken into account, the chosen limit was based on the experience of the investigators.

Other choices were made in similar manners for parameter limits used in the decision algorithm. A maximum torque limit to allow torque reserve was implemented by limiting the maximum rack position. This was implemented in the gear selection aid by recommending a gear only if the estimated digitized rack position was below 140. (Maximum rack position from the shaft encoder during performance mapping was 154, with 140 being approximately 91% of 154.) The performance mapping results indicated the constant rack tended to follow the torque curve, thus a constant rack value was initially used as the gear selection aid limit. It was noted earlier this resulted in an inappropriate recommendation to one operator. For this reason an equation was developed and used in the simulation program to estimate the maximum rack position at a given engine speed.

The initial attempt at developing a maximum rack equation performed regression analysis on 16 points of 100% torque load data from the PTO performance mapping. The resulting equation predicted rack values slightly high for engine speeds below approximately 1700 rpm. Potentially the equation could have the same problem it was intended to remedy. An extra data point at

90% torque load and 1400 rpm from the engine performance mapping was added as a 17th data point. Regression analysis performed with the extra data point yielded equation [7], which

$$MAXRK = -40.7732 + 0.1885553*RPM \\ -0.000461812*RPM*RPM \quad [7]$$

estimates rack values slightly lower than the observed maximum for the slower engine speeds. The performance map in Figure 4 shows the 17 points used to develop the equation and the resulting 95% rack limit obtained by multiplying the result from equation [7] by 0.95. The constant rack at value 140 is also shown for comparison.

An additional portion of the gear selection algorithm compared the next gear lower than the gear with optimum fuel savings to the optimum gear. If use of the lower gear resulted in less than an additional 0.6 kg/h (0.2 gal/h) fuel consumption, then the lower gear was considered as optimum because of its additional torque reserve. A 1.6 kg/h (0.5 gal/h) minimum fuel savings threshold was chosen above which a recommendation was made to shift up for fuel savings. If the optimum gear lowered fuel consumption from the current rate by more than the threshold, a recommendation was made to shift up and throttle back.

A computer program was developed to examine the parameter limits. The program written in 'C' language was compiled and executed on a DEC VAX 11/750 computer. The field data recorded by the gear selection aid were used as input for field load and ground speeds for the simulation program. The program repeated

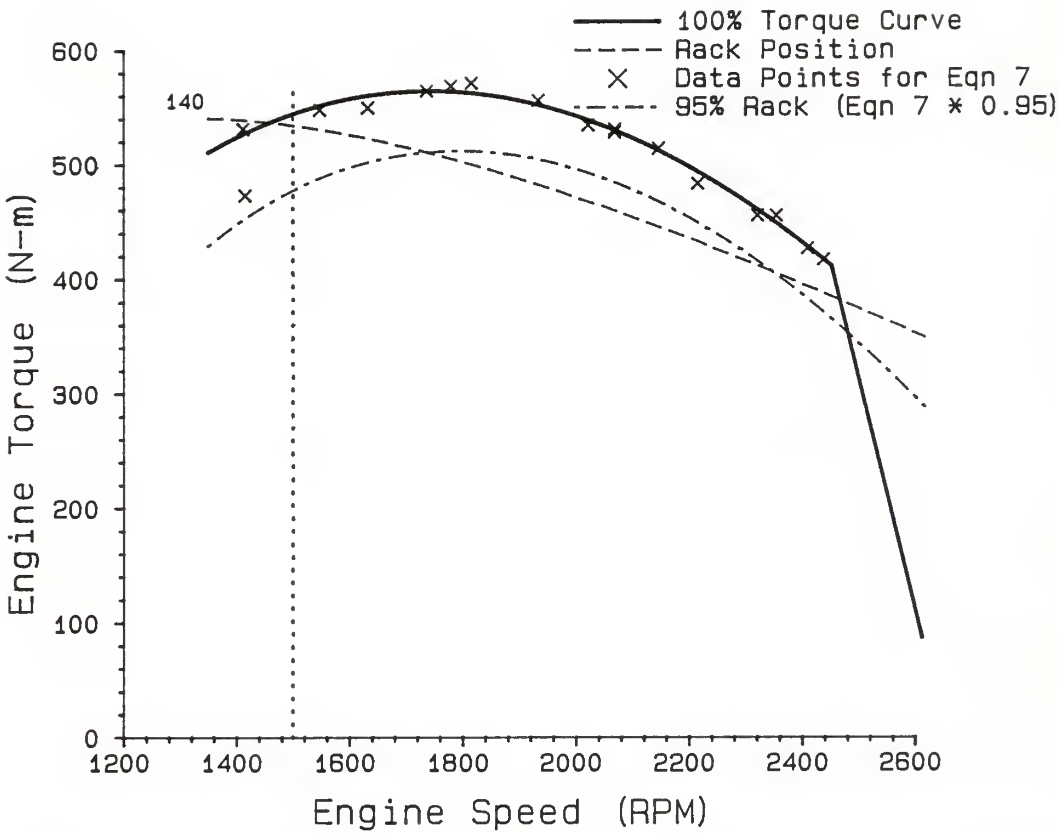

Figure 4. Engine torque versus speed with constant rack value of 140 and 95% of value from maximum rack equation [7].

the logic used in the gear selection aid decision algorithm. The parameter limits within the logic were varied to determine the effect on the shift frequency and the resulting fuel efficiency for the field data. The varied parameters included lower engine speed, maximum rack position, minimum fuel savings to recommend a gear shift, maximum additional fuel consumption to use next gear lower than optimum, and length of time period over which the data were averaged. An additional portion of the program used a different algorithm for deciding when to shift up. It integrated

the potential fuel savings between gears had the next higher gear been used. A shift to a higher gear was recommended when the potential savings reached a minimum threshold value. For computing fuel efficiency and shift frequency the simulation program assumed each shift recommendation was followed by the operator.

The program, included in Appendix B, was developed in three stages. The first summarized actual operator performance and compared it to the performance had the gear selection aid been followed completely. This was followed by a program changing each parameter value except the time period to determine the effect on the frequency of shifting and the fuel consumption. The third version averaged the data over time periods ranging from 4 seconds to 15 minutes to analyze the effect on shift frequency and fuel consumption.

The names in Appendix B refer to the file names containing the source code. Names ending with '.h' are header files that contain definitions and variable declarations. The '.c' ending indicates the file contains source code written in 'C' programming language. A '.c' file with the statement "#include name.h" as the first line, where 'name' represents one of the header files, could access the variables and definitions in that header file. This provides a means for programs and subroutines to access and share the same global variables and information.

An effort was made to keep the program general, with a minimum of files specific to the engine and transmission of the

IHC model 3588 tractor. Running this program for another engine and transmission combination may require modifying up to four files, two header files and two files with program subroutines. The definitions in engine.h and tr.h header files need to be changed to reflect the engine and transmission characteristics. The subroutines collected under model.c also require tailoring to fit the engine. The nxrec.c subroutine was written to fill the data structure with a one minute data point from the data files recorded by the Gear Selection Aid. A second version of nxrec.c read and placed 4 second data into the data structure. Should data files other than those from the gear selection aid be used for input, nxrec.c may require modification. The data files contained all the values needed to fill the data structure. With the routines in model.c, only three values (rack position, engine speed and transmission output speed) are required input from the data file. The remaining values could have been calculated from these three values.

The tr.h and trih.h header files contain the gear ratio tables for the transmission. The actual transmission ratios available on the IHC model 3588 tractor are in trih.h. Early work with the simulation program quickly showed that the difference in gear ratios between first gear, high torque amplifier, high range and second gear, low torque amplifier, high range easily overshadowed the changing of other parameters. The change between these two successive transmission gear ratios was in excess of 25%. In order to have any possibility of a shift to

the higher gear setting, the engine rpm had to be in excess of 2010 rpm in the lower gear with the lower engine speed limit set at 1500 rpm. Reviewing the data quickly showed that, for the ground speeds used by most of the operators, the most commonly recommended gears were first gear and high range, with either high or low torque amplifier setting. A setting using second gear was rarely recommended because the engine speed would be below the 1500 rpm limit.

To prevent this large ratio change between gears from overshadowing the other parameters, a hypothetical transmission was developed with a 15% change between each gear ratio. The hypothetical transmission ratios are in the tr.h header file. An examination of several recent tractor models with 15, 16 or 18 transmission gears in the Nebraska tractor tests showed several with ground speeds that varied from 13% to 16% between successive gears. Thus the revised ratios were considered reasonable at 15% increments. The ratios were computed from an arbitrary starting ratio of 20.0, with ratios going down and up from this point. The simulation program was run using the hypothetical transmission ratios.

The program listing in appendix B contains three files with main programs to allow for executing different variations of the program. The first version called gearsum.c summarizes the results within the field data, including the number of recommendations by the gear selection aid. It was mainly used to develop and verify several of the subroutines used in the other program

versions.

The second version called gearth.c determines the number of shifts and the resulting fuel consumption as threshold parameters are changed. A shift was counted each time the decision algorithm recommended shifting from the previously chosen gear, or when required to return operating conditions within the parameter limits. The gear selected for the ground speed and load associated with the current data period became the previously selected gear for the next data period. The fuel consumption information was summarized in the previously chosen gear at the current operating conditions, unless a shift was required to stay within the operating limits. The attempt was to use fuel information for the most likely used gear during the current period.

Threshold parameters examined in this program include low engine speed limit, maximum rack limit, minimum fuel saving threshold to recommend a shift, maximum fuel loss to use next lower gear instead of optimum, and an alternate method of deciding the fuel saving threshold. The alternate method computed an incremental fuel loss between gears for not using the next higher gear. Lost potential fuel savings between successive gears were summed in accumulator variable, effectively integrating fuel losses between gears over time. When the accumulated incremental fuel loss became greater than the threshold value a shift up and throttle back recommendation would be made. The accumulator between gears was cleared (set to zero) when the next higher gear resulted in values outside the parameter limits. This decision

algorithm would avoid a condition in which a gear was continually just below a minimum fuel saving threshold, so it would not be recommended, though it could be used and would save fuel.

The other threshold parameters varied within the gearth.c program changed the limits within the decision algorithm actually used by the gear selection aid. Each parameter was varied individually, leaving the other parameters at set values. The set values for the parameters were the same as used in the gear selection aid with the exception of the maximum fuel loss to use the next gear lower than the optimum. Table 5 contains the range, increment size, and set value when the variable was held constant for each varied parameter. The different time periods over which the data were averaged are also included.

Table 5. Range and increment values for parameters varied within simulation programs.

Parameter	Set	Minimum	Maximum	Increment
Saving threshold (kg/h)	1.6	0.0	4.0	0.1
Maximum Rack (%)	95.0	80.0	100.0	1.0
Minimum speed (rpm)	1500.0	1300.0	1700.0	25.0
Max. use lower gear (kg/h)	0.0	0.0	4.0	0.2
Accumulated loss (kg)	---	0.0	2.0	0.025
Time, 4 sec. data (sec)	---	4.0	60.0	4.0
Time, 1 min. data (sec)	60.0	60.0	900.0	60.0

The gearavg.c program in appendix B, the third main program, averages the data over different time periods to determine the effect on fuel savings and shift frequency. Field data from the gear selection aid were stored on cassette tape with fifteen 4 second averages every fifth minute, and one minute averages for the four minutes between. With this data available, the average

times used were in multiples of four seconds from 4 seconds to 60 seconds, and multiples of one minute from 1 minute to 15 minutes. Time periods longer than 15 minutes were not considered timely information for operator feedback. Because the data containing four second information was recorded only every fifth minute, for the 60 second time periods the result from the four second data cannot be directly compared to the result from the continuous one minute data. But the results from both data should show similar trends.

The program versions in gearth.c and gearavg.c determined the possible tractor settings for the ground speed and loading conditions read from the field data files. The program then began a series of checks to see what action should have been taken by the operator, either following recommendations to save fuel or bringing operating conditions within parameter limits.

The first conditions checked were the engine speed and rack position for the previously chosen gear and current operating conditions. If the operator increased ground speed since the preceding period, the engine speed could be above the maximum possible speed if the gear from the preceding time period was too low. In this case the operator had to shift up to obtain the ground speed. The fuel information was updated assuming the operator used the lowest gear resulting in an engine speed below the maximum rpm limit during the time period. The shift information was updated to reflect the gear and a shift counted. The program waited till the next period or program pass to look for a

shift recommendation.

If the engine speed was below the minimum rpm limit or the rack position above the maximum position limit, a shift down was necessary to increase engine speed and reduce torque loading. The shift information and the fuel information were updated assuming that the operator shifted down to maintain either power or engine speed. The values used to update information were for the highest gear that met the engine speed and rack position limits. Should operating conditions be such that no gear was within the rack limit, the gear with the highest engine speed within the the maximum speed limit was chosen for engine power output. The gear choice was recorded in a previous gear variable for use during the next program pass, which would be using the next time period from the field data file. A shift was counted and the fuel information updated in the gear just selected.

The proceeding conditions combined to assure that the tractor operation was within the limits of the performance map, or action as described was taken to bring operation back within the limits. The first check was for the upper engine speed limit. The second check was the lower engine speed and the high torque limit, using the rack position to check the latter. An earlier check of the incoming data verified that the data had a minimum power load, which was specified in the engine.h header file.

If the operating conditions were within the limits, the remaining check was to see if a shift could be made from the

current gear that would result in a fuel savings greater than the threshold limit. If a shift met the threshold criteria the shift information was updated to the new gear. Whether a shift up was made or not, the fuel information was updated using fuel consumption for the current operating conditions from the field data in the previously chosen gear. In no case was allowance made for extra fuel consumption during a shift.

With repeated calls to the subroutines the program analysis was made for each time period with valid field data. The printing subroutines completed the computations regarding the fuel and shift information, and printed the results. The printed information contained the value of the changed parameter, the number of time periods that were analyzed, the number of shifts that would result from following every recommendation, the average specific fuel consumption and the average fuel consumption over the entire analysis.

Simulation Program Evaluation and Results

The summary programs ran initially used the same decision algorithm, parameter limits and transmission gear ratios as the gear selection aid program. The results showed that of the 3668 recorded minutes with the display off the tractor could have been operated at shift up and throttle back settings for 1993 of the minutes. Changing gears would have saved more than 1.6 kg/h of fuel 59.2% of the time.

The 8788 comparison minutes with the display on showed that 2568 minutes could have been operated at shift up and throttle back settings, or 29.2% of the time. The percentage of time with potential savings was almost halved with the gear selection aid making recommendations. The discussion of field operation of the gear selection aid pointed out that one operator ignored the recommendations and others did not always follow the exact recommendation for various reasons. With these considerations, the reduction of operating time at settings with fuel use higher than optimum showed a large improvement when the gear selection aid was used.

A portion of the time that was not at the optimum setting, was expected to be at shift up and throttle back settings from those settings selected without the gear selection aid. Adding to the summary program the statements to average specific fuel consumption while recommendations could be made showed that the operators decreased fuel consumption by 5.2% with the display on. While the display was off and shift up and throttle back settings could have been used, the optimum gear would have reduced specific fuel consumption by 17.4% from that obtained by the operators. When the display recommendations were not being followed exactly, the recommendations may have helped the operators reduce fuel consumption and realize approximately one-third of the possible savings.

Two program versions determined the result from changing the parameters. The outputs were plotted as specific fuel

consumption in grams per kilowatt·hour versus shift frequency in shifts per hour to maintain optimum settings. The seven varied parameters were threshold savings, rack limit, minimum lower engine speed, maximum loss to use next gear higher than actual optimum, threshold accumulated loss in the alternate decision algorithm, and two time averages, one based on the one minute data and one on the four second data. In general, as the frequency of shifting decreased, the specific fuel consumption increased with one notable exception.

The exception came from changing the time period over which data was averaged. As could be anticipated, Figure 5 shows a longer time period reduced the frequency of shifting to maintain optimum settings. However, fuel consumption did not increase, but decreased slightly as the time period increased. Further examination revealed the result was due to the nonlinearity of the specific fuel consumption on the engine performance map. As the percent of maximum torque decreases at an engine speed, the specific fuel consumption increases at an increasing rate.

As an extreme example, if the tractor operates one minute at conditions causing 400 N·m engine torque at 1800 rpm the resulting specific fuel consumption is approximately 254 g/kW·h, as shown previously in Figure 2. Should the torque for the next minute be 200 N·m, at the same speed the specific fuel consumption is 308 g/kW·h. For the two one minute periods the average specific fuel consumption is 281 g/kW·h. But for a two minute period containing these one minute periods the average torque

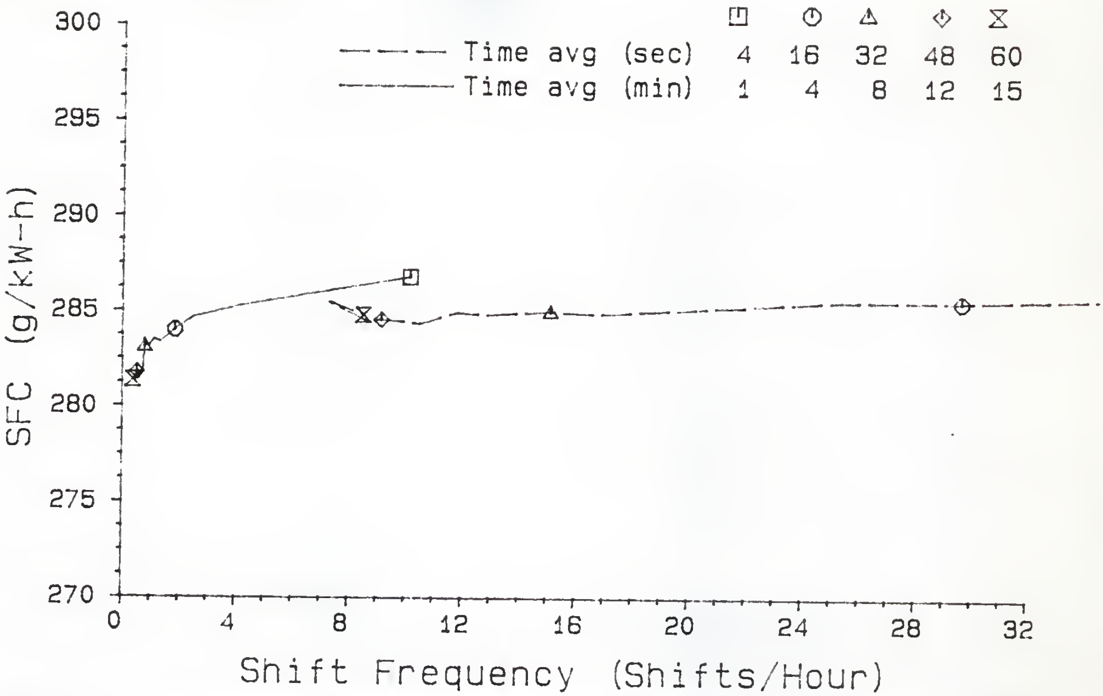

Figure 5. Specific fuel consumption versus shift frequency as data averaging time period changes.

load is 300 N·m. The specific fuel consumption for 300 N·m torque load at 1800 rpm is 269 g/kW·h. A 12 g/kW·h reduction in specific fuel consumption appeared by increasing the length of the time averaging period as a result of the nonlinear nature of the specific fuel consumption. Variations in engine speed cause the same result, though the apparent reduction is less.

An additional contributing factor may result from rejected data during the longer time periods. Typically, when placing a load on the tractor, an operator will ease into the load. When stopping an attempt will be made to reduce the load, possibly by steering into already tilled ground, reducing the implement depth or reducing ground speed. The lower loading typically results in

higher specific fuel consumption when starting or ending field work. The longer time periods will reject the data period because the tractor was stopped during the period, tending to reduce the overall specific fuel consumption average in relation to the shorter time periods. The shorter time periods include more time with high specific fuel consumption possibly raising the overall specific fuel consumption average.

The relation of specific fuel consumption and shift frequency for the remaining parameters are graphed in Figure 6. The specific fuel consumption generally increased as the shift frequency decreased with the parameter variation.

Variation of the maximum rack limit during heavy loading greatly affected the specific fuel consumption and shift frequency change. When operating conditions did not reach the maximum rack value the variation had no effect. For the best fuel economy, the program results indicate that using 100% rack limit would cause a slight increase in the shift frequency and a small reduction in specific fuel consumption. The rapid specific fuel consumption changes occur in the lower torque ranges on the performance map. Use of 100% rack limit does not consider engine lugging and overloading. The results indicate the highest possible rack limit that avoids these conditions should be used for optimum fuel savings.

The use of the next gear lower than the optimum increased the specific fuel consumption, as could be anticipated. As the

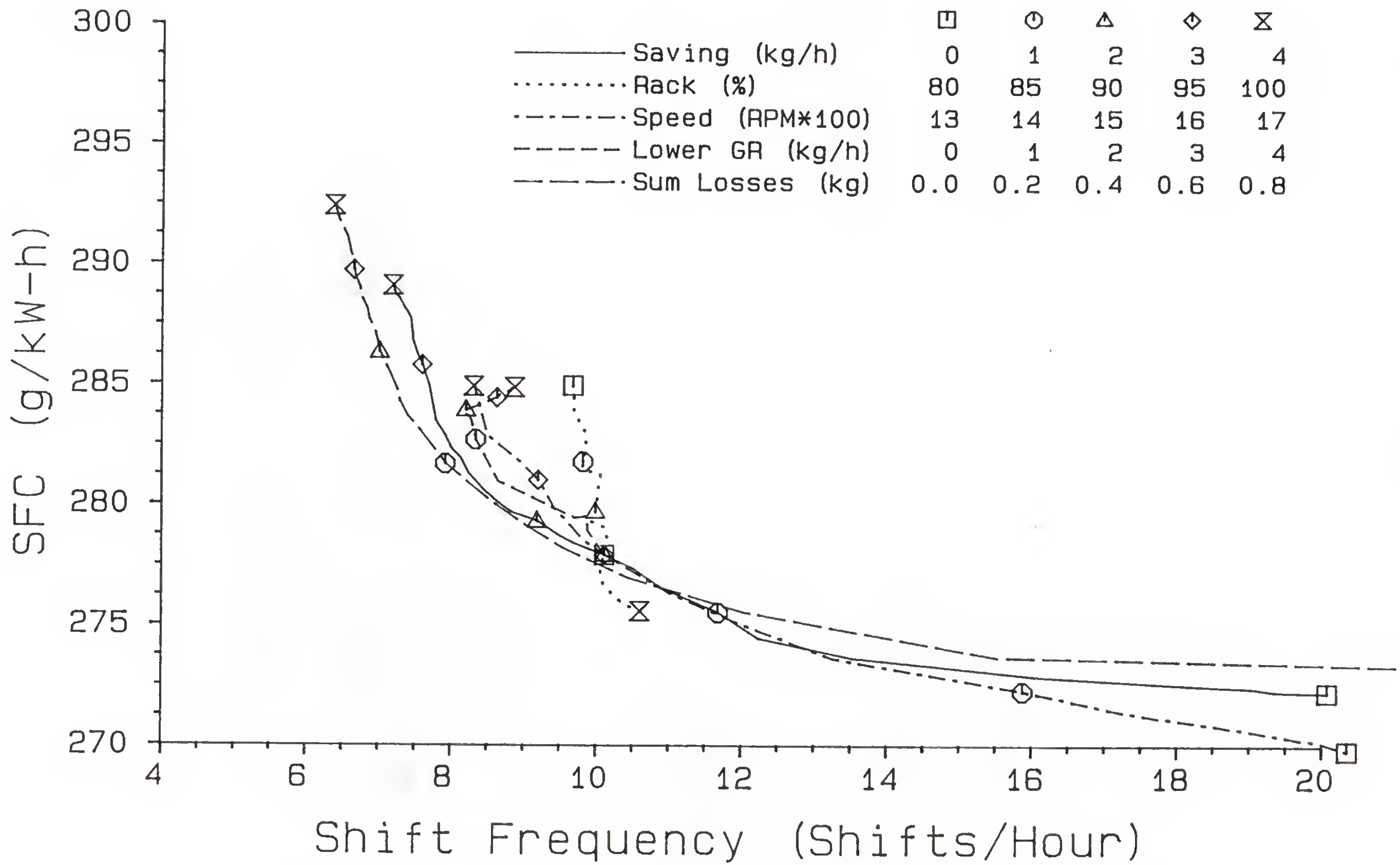

Figure 6. Specific fuel consumption versus shift frequency relation as parameter limits are changed.

limit was increased where the next higher gear was used the shift frequency decreased to a point, then begin increasing again after reaching some tolerance point. The tolerance point tended to vary from 1 kg/h up to 2 kg/h. The reduction in shift frequency may be a sign that shift ups are reduced that must shortly be followed by a shift back down.

Reducing the lower engine speed limit from 1500 to 1300 rpm reduced the specific fuel consumption slightly, but doubled the number of shifts required to stay at the optimum. Raising the limit to 1700 rpm did not have as dramatic an effect, but the shift frequency did drop some. The lower limit on engine speed should be considered for the number of shifts that will be required to stay above the limit.

The alternate decision algorithm which integrated the loss over time between gears was consistently the lowest or close to the lowest specific fuel consumption at a given shift frequency. The algorithm is worthy of further consideration for use in decision algorithms of when to shift up. The algorithm results showed a distinct upturn were the specific fuel consumption began to increase rapidly. The algorithm also had results very close to those from constant values for the other parameters with the original decision algorithm.

The chosen parameters used in the decision algorithm appear reasonable, even with the changes made for the program in the transmission ratios and maximum rack computation. The results

from this simulation indicate the next lower gear choice may have been helpful in reducing the number of shifts.

A portion of the program was used to summarize the shift frequency and specific fuel consumption performance of the operators. Originally this was included in the program as a reference to determine if the results were reasonable. The operator's average shift frequency was surprisingly high at 11.4 shifts per hour for the more than 266 hours of one minute data, a shift every 5 1/4 minutes. An operator shift was counted any time the gear ratio changed from the ratio of the proceeding time period more than a gear ratio tolerance limit, which may include some momentary clutch depressions. The operators ranged from a low of 1.5 to a high of 30.7 shifts per hour. The latter regularly shifted the torque amplifier between low and high, which is an "on the go" shift. The intuitive notion that the tractor runs for extended time periods in a set gear and at a set throttle did not hold for the operators in this research. Several operators had higher shift frequencies in their field operation than was predicted at the set values for parameter limits by the simulation program.

The program results at the parameter values used in the gear selection aid generally yielded lower specific fuel consumption than the operators actually achieved, as might be anticipated. Two operators had conditions were they achieved the lower specific fuel consumption. It is possible that the hypothetical transmission gears for the simulation program resulted in

settings not quite as favorable as those from the actual tractor in the actual conditions of these operators. Both operators achieved the better setting while the gear selection aid display was on and able to make recommendations.

CONCLUSIONS

1. An effective gear selection aid can be developed using only inputs of engine speed, transmission output speed, and injection pump plunger sleeve pin position.

2. The EGT can be used as an alternate input for determining current operating conditions. The accuracy achieved with the EGT in this system would be lower than using the plunger sleeve pin position, partially a result of lower measurement resolution.

3. Fuel savings produced by such a system varies greatly, but the average saving experienced by the ten operators in this study was 12.5%.

4. The simulation summary, using the hypothetical transmission gear ratios and the maximum rack equation, indicated the parameter limits chosen for use in the gear selection aid were reasonable. The simulation showed that the decision algorithm which integrated lost potential fuel savings between gears would have typically resulted in lower specific fuel consumption at the same shift frequency. Because of the non-linearity of the specific fuel consumption over the engine performance map, averaging the loading over longer time periods gives the appearance of reducing specific fuel consumption.

SUMMARY

The gear selection aid showed a range of fuel savings over ten operators. The potential for savings depended upon the initial tractor settings the operator used and the implement draft, plus the willingness to follow shift up and throttle back recommendations. Fuel savings attributed to the gear selection aid ranged from over 30% down to none. The average savings for the ten operators was 12.5%.

The simulation program results generally indicate the parameter limits within the original decision algorithm were reasonable values. Lengthing the time period over which the tractor inputs are averaged reduces the predicted specific fuel consumption. The reduction resulted from the non-linearity of the specific fuel consumption over the engine performance range and data rejection of the relatively high specific fuel consumption minutes immediately before stopping and after starting the tractor with the longer time periods. The other parameters tended to increase fuel consumption as the shift frequency decreased.

AREAS FOR FUTURE RESEARCH

A future extension to this project is to extend the gear selection aid from an open loop feedback system through the operator to a closed loop system directly controlling the transmission and throttle settings. A smooth shifting or continuous transmission, such as a hydrostatic or a mechanical continuously variable transmission, would probably give the best results.

Several areas could be studied further for the relationship to shift up and throttle back operation. This study changed only one parameter at a time. An evaluation of all the parameters simultaneously would be much more complicated, but nearer to the actual field system needs. All parameter limits were considered absolute here, but a hysteresis around the limit values should reduce the shifting frequency. More evaluation could be made to determine at what percent of maximum torque the engine will become most susceptible to overloading conditions.

Another area of interest is what affect on engine life does shift up and throttle back settings have. The shift up and throttle back principle would probably be accepted quicker if owners and operators are sure the tractor life will not be shortened. The simulation program could be applied to other engines to determine if the results are similar.

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APPENDIX

Appendix A

1982 Mathematical Models Relating Engine Parameters.

$$kWhat = 1.54423 + (0.017821*rpm) + (1.253986*rack) - (0.000023346*rpm^2) + (0.000752175*rpm*rack) \quad [1]$$

"F" statistic = 2804, r squared value = 0.9968

$$ffhat = 20.56249 + (0.007573*rpm) + (0.267594*rack) - (0.000002502*rpm^2) + (0.00090578*rack^2) + (0.000114211*rpm*rack) \quad [2]$$

"F" statistic = 2637, r squared value = 0.9973

$$rackhat = -1.310154 - (0.015853*rpm) + (0.825427*kWhat) + (0.000027 79667*rpm^2) - (0.0004996*rpm*kWhat) \quad [3]$$

"F" statistic = 2129, r squared value = 0.9958

where:

kWhat = predicted pto kW - 77.95
rpm = engine rpm - 1921.51
rack = encoded rack position - 128.054
ffhat = predicted fuel flow (kg/hour)
rackhat = predicted encoded rack - 128.054

The subtracted values were the average values for the parameters from the 1982 performance mapping.

Appendix B

```
# Makefile for compiling the gear simulation programs
# giving the file dependencies.

gearsum: gearsum.o nxrec.o model.o gearup.o copydata.o
     cc gearsum.o gearup.o model.o nxrec.o copydata.o -o gearsum

gearavg: gearavg.o nxrec.o model.o gearup.o
gearavg: copydata.o tavg.o thsub.o
     echo "BASE_TIME should be 60 sec"
     cc gearavg.o tavg.o gearup.o model.o nxrec.o copydata.o \
          thsub.o -o gearavg

sgravg: gearavg.o nxrec2.o model.o gearup.o
sgravg: copydata.o tavg.o thsub.o
     echo "BASE_TIME should be 4 sec"
     cc gearavg.o tavg.o gearup.o model.o nxrec2.o copydata.o \
          thsub.o -o sgravg

gearth: gearth.o nxrec.o model.o gearup.o copydata.o
gearth: thold.o printth.o thsub.o initth.o
     cc gearth.o gearup.o model.o nxrec.o copydata.o thold.o \
          printth.o thsub.o initth.o -o gearth

gearup.o: tr.h trih.h

gearsum.o gearth.o gearavg.o gearup.o copydata.o tavg.o: gear.h
thold.o printth.o thsub.o nxrec.o nxrec2.o bugger.o: gear.h

gearavg.o thold.o printth.o thsub.o initth.o bugger.o: thold.h

gearsum.o gearth.o gearavg.o gearup.o tavg.o: engine.h
thold.c printth.o thsub.o initth.o: engine.h
```

```
/* Engine and transmission parameter definitions */

     /*highest normal speed for engine         */
#define FULL_RPM          2600.
     /*low limit stop for engine rpm           */
     /*during gear up iteration                */
#define LIMIT_LOW_RPM     1500.
     /*lowest acceptable operating speed,      */
     /* should be equal or lower than          */
     /* rpm in above Limit_low_rpm             */
#define MINIMUM_RPM       1300.

     /*normal fractional limit on rack to      */
     /* prevent engine overload.               */
     /* Multiplier for maxrack() value.        */
#define LIMIT_HI_RACK     0.95
     /* fuel saving threshold in kg/hr         */
     /* between current gear fuel use          */
     /* and higher gear, a larger difference */
     /* will shift to higher gear              */
#define LIMIT_FUEL_SAV    1.60

     /*lowest reasonable power in kW,          */
     /* lower input data is rejected           */
#define LOW_POW           5.
     /*highest reasonable power in kW          */
     /* higher input data is rejected          */
#define HI_POW      116.

     /* low ground speed, 3kph was low in      */
     /* gear selection data                    */
     /* lower input data is rejected           */
#define LOW_SPEED   5.
     /* top ground speed, 16kph from data      */
     /* higher input data is rejected          */
#define TOP_SPEED   16.

#ifdef IH
     /*number gears in in transmission ratio */
     /* table, 16 for actual IH tran           */
#define NO_GEARS     16
     /*no of gear above which are road gears */
#define ROAD_GR      12
#else
     /*for hypothetical transmission           */
#define NO_GEARS     18
     /*no of gear above which are road gears */
#define ROAD_GR      14
#endif

     /*lowest transmission gear ratio          */
#define LOW_GR_R     42.2041
     /*highest gear, note: ratio is ehz/thz  */
```

```
#define HI_GR_R     3.7714
     /* + or - tolerance used to check for   */
     /* a change in gear ratios              */
#define GEAR_TOL    0.25

     /* seconds in base time period          */
     /* 60 for one minute data, changed to   */
     /* 4 for four second data               */
#define BASE_TIME   60
```

```
#include <stdio.h>
#include <assert.h>

int  yr,mo,dy,hr,min,sec;     /*time records */
FILE *lptr;          /*to location data file  */
FILE *fopen();
struct data {
     float thz;      /* transmission hertz    */
     float ehz;      /* engine hertz          */
     float tr;       /* tran ratio            */
     float rack;     /* fuel pump setting     */
     float rpm;      /* engine rpm            */
     float kph;      /* ground speed kph      */
     float kw;       /* power kilowatts       */
     float ff;       /* fuel flow KG/H        */
     float sfc;      /* bsfc g/kWh            */
};

     /* hold gearup results, need space for  */
     /* each gear plus a at least 1 more     */
struct data upshift[20];
     /* hold current gearup ratio            */
float upgrratio;
     /*subroutine to choose gear for min rpm */
     /*and max rack,returns ptr into upshift */
struct data    *choose_gear();

     /* groups of 15 1min or 4sec avgs.      */
struct data mdata[15];
     /* place for averaged data of changing  */
     /* time period lengths                  */
struct data avgdata;

     /* functions in model.c that return     */
     /* double values                        */
double    rkhat(),kW(),fflow(),maxrk();
double    ehz_rpm(),thz_kph();
```

```
     /* define for the various threshold      */
     /* parameters of interest the minimum    */
     /* value, maximum value, and the         */
     /* increment of value.  Elem is the      */
     /* number of elements that will result   */
     /* from the other values, plus one       */
     /* used for locating end of arrays       */
#define MIN_SAV     0.0
#define MAX_SAV     4.01
#define INC_SAV     0.1
#define ELEM_SAV    42

#define MIN_RACK    0.8
#define MAX_RACK    1.00
#define INC_RACK    0.01
#define ELEM_RACK   22

#define MIN_RPM     1300.
#define MAX_RPM     1700.1
#define INC_RPM     25.
#define ELEM_RPM    18

#define MIN_LGR     0.0
#define MAX_LGR     4.01
#define INC_LGR     0.2
#define ELEM_LGR    22

#define MIN_SUM     0.0
#define MAX_SUM     2.001
#define INC_SUM     0.025
#define ELEM_SUM    82

/*
 * Structure for accumulation of threshold results
 *   including: threshold value,
 *        shift count for the value,
 *        specific fuel consumption,
 *        previous gear for comparison,
 *        and running total of fuel for gear used
 */

struct thold {
     double    value;    /* thresh-hold value              */
     int       shift;    /* shift count                    */
     double    sfcsum;   /* accumulate the sfc values      */
     int       sfcct;    /* sfcsum count, for avg sfc      */
     double    gear;     /* optimum gear previous loop     */
     double    fuel;     /* accum. actual fuel use, kg     */
};

     /*for tracking operator actual performance    */
struct thold   operator;
```

```
     /*for finding worst case performance    */
     /* at full engine speed                 */
struct thold   fullrpm;

     /*min threshhold fuel savings for shift */
struct thold   savings[ELEM_SAV];
     /*max rack setting allowed for power    */
struct thold   rack[ELEM_RACK];
     /* low rpm limit                        */
struct thold   engrpm[ELEM_RPM];
     /* use next lower gear if loss from     */
     /* opt. gear is less than value         */
struct thold   lastgr[ELEM_LGR];
     /* to shift up must accumulate a minimum     */
     /* loss, loss reset to Ø. when in right */
     /* gear or at time of a shift           */
struct thold   sumloss[ELEM_SUM];

     /*running total of fuel loss between gears from    */
     /*not shifting. 1st size should be same as         */
     /*specified for sumloss above, 2nd larger than     */
     /*the number of gears in tr.h           */
float     ffloss[ELEM_SUM][NO_GEARS];
```

```
#ifdef    IH   /* allow use of IH gears with cc -DIH    */
#include "trih.h"
#else
/* Hypothetical transmission ratios developed to avoid
 * the large jump in the IH3588 between hi hi 1 and hi lo 2
 * (over 25% change.) Ratios were set to have a 15% change
 * between transmission ratios for gears 3 thru road gear.
 */

float     gratio[] = {
                42.2041,
                36.0787,
                26.45,
                23.00,
                20.00,
                17.39,
                15.12,
                13.15,
                11.435,
                9.944,
                8.647,
                7.519,
                6.538,
                5.685,
                5.2333,    /* Road gears              */
                4.4738,    /*3rd gear,hi TA, hi range    */
                4.4117,    /*4th gear,lo TA, hi range    */
                3.7714,    /*4th gear,hi TA, hi range    */
        };
#endif
```

```
     /* transmission gear ratio table for IH3588 2+2    */
     /* tractor, ratios are THZ / EHZ                    */
float     gratio[] = {
               42.2041,  /*1st gear,lo TA, lo range    */
               36.0787,  /*1st gear,hi TA, lo range    */
               26.8953,  /*2nd gear,lo TA, lo range    */
               22.9918,  /*2nd gear,hi TA, lo range    */
               18.2841,  /*3rd gear,lo TA, lo range    */
               15.6304,  /*3rd gear,hi TA, lo range    */
               15.4137,  /*4th gear,lo TA, lo range    */
               13.1766,  /*4th gear,hi TA, lo range    */
               12.0797,  /*1st gear,lo TA, hi range    */
               10.3265,  /*1st gear,hi TA, hi range    */
               7.6980,   /*2nd gear,lo TA, hi range    */
               6.5808,   /*2nd gear,hi TA, hi range    */
               5.2333,   /*3rd gear,lo TA, hi range    */
               4.4738,   /*3rd gear,hi TA, hi range    */
               4.4117,   /*4th gear,lo TA, hi range    */
               3.7714,   /*4th gear,hi TA, hi range    */
     };
```

```
#include "engine.h"
#include "gear.h"

/* main routine to summarize data and compare actual operator
 * performance to Gear Selection Aid recommendations.
 * also reports reasons for stopping gear up iteration.
 */

main(argc,argv)
int argc;
char *argv[];
{
     int ct,grup,upsav;  /* count minutes in analysis        */
                         /* how many w/ gearup and saving    */
     int count[5];       /* record reason gearup() quit      */
     int shifts;         /* count # gear shift from current  */
     register struct data *d,*updat;
          /* pointers to speed up access to data structures */
     register int i,num; /* fast counters for loops          */
     struct data *nowd;  /* ptr to current data in upshift   */

     d = mdata;          /* set ptr to mdata structure       */
     while (--argc > 0){ /* loop thru named data files       */
          if ((lptr=fopen(*++argv,"r"))==NULL){
               fprintf(stderr,"gear: cannot open %s\n",*argv);
               exit(1);
          }
          ct = grup = upsav = 0;   /* zero counters          */
          for (i=0; i<5; i++)
               count[i]=0;
          while (nxrec(d) > NULL){ /* loop while have data   */
               if ((d->kph < LOW_SPEED) || (TOP_SPEED < d->kph)){
                    continue;      /* check ground speed     */
               }
               if (d->kw < LOW_POW || d->kw > HI_POW) {
                    continue;
               } /* avoid very low power, causes high sfc    */
               updat = upshift;    /* set ptr to upshift     */
               upgrratio = d->tr;  /* init gear ratio        */
               shifts = -1;   /* pre-incremented in loop     */
               do{            /* gearup till reach a limit   */
                    shifts++;
                    num = gearup(d->thz,d->kw, upgrratio,updat);
                    upgrratio = updat->tr;
               } while (num == 0);
               ++count[num];  /* what stopped gearup         */
               ct++;          /* count time periods          */
               if (shifts > 0){
                    grup++;   /* possible gear up,incr ctr   */
                    if ((d->ff - updat->ff) > LIMIT_FUEL_SAV)
                         upsav++;  /*save > limit, so count */
               }
          }
```

```
        printf("\n%s\nminutes analyzed- %d\n",*argv,ct);
        printf("gearup() results\n");
        printf("  <1500rpm-\t%d\n",count[1]);
        printf("  >95%%rack-\t%d\n",count[2]);
        printf("  road gear-\t%d\n",count[3]);
        printf("  ratio out of range-\t%d\n",count[4]);
        printf(" minute w/gearup(no fuel check)-%d\n",grup);
        printf(" minute w/gearup, save %.2fkg/h)-%d\n",
                       LIMIT_FUEL_SAV,upsav);
        fclose(lptr);
    }
}
```

```
#include "engine.h"
#include "gear.h"

main(argc,argv)
int argc;
char *argv[];
{

     int ct;               /* count minutes in analysis        */
     int shifts;           /* count # gear shift from current */
     register struct data *d,*updat;
          /* pointers to speed up access to data structures */
     register int i,num; /* fast counters for loops         */
     struct data *nowd;  /* ptr to current data in upshift  */

     d = mdata;            /* set ptr to data structure       */
     while (--argc > 0){ /* loop thru named data files      */
          initth();        /* call sub to init threshold var  */
          ct = 0;
          if ((lptr=fopen(*++argv,"r"))==NULL){
               fprintf(stderr,"gear: cannot open %s\n",*argv);
               exit(1);
          }
          while (nxrec(d) > NULL){
               if ((d->kph < LOW_SPEED) || (TOP_SPEED < d->kph)){
                    continue; /* check ground speed */
               }
               if (d->kw < LOW_POW || d->kw > HI_POW) {
                    continue;
               } /* avoid very low power, causes high sfc   */
               updat = upshift;    /* set ptr to struct     */
               upgrratio = LOW_GR_R;    /* start at low gr  */
                    /* fill init value in up data structure */
               data_calc(d->thz,d->kw,upgrratio,updat);
               do{  /* fill in ratios lower than current gr */
                    ++updat;
                    gearup(d->thz,d->kw,upgrratio,updat);
                    upgrratio = updat->tr;
               }while (upgrratio > d->tr);
               copydata(d,updat);  /* mv current data to up */
               nowd = updat;       /* set ptr to this place */
               upgrratio = d->tr;  /* init ratio for gearup */
               shifts = -1;   /* init ctr, pre-incr in loop */
               do{  /* fill in remaining upshift to min rpm */
                    ++updat;
                    shifts++;
                    num = gearup(d->thz,d->kw, upgrratio,updat);
                    upgrratio = updat->tr;
               }while (updat->rpm >MINIMUM_RPM && num != 4);
               if (num != 4){ /* num != 4, good gear ratio  */
                         /* give upshift to threshold sub   */
                    thold(nowd,shifts,BASE_TIME);
                    ct++;     /* count minutes in analysis  */
```

```
                }
            }
            printf("\n%s\nminutes analyzed- %d\n",*argv,ct);
            printth(BASE_TIME);
            fclose(lptr);
        }
}
```

```
#include "engine.h"
#include "gear.h"
#include "thold.h"


main(argc,argv)
int argc;
char *argv[];
{
     register struct data *d,*updat,*avgd;
          /* pointers to speed up access to data structures */
     struct data *nowd;  /* ptr to current data in upshift  */
     register int i;     /* fast counters for loops         */
     int  shifts;   /* count # gears can shift from current */
     int  period;   /* number of data points in averaging   */
     int  num;           /* general variable for ctr,etc.   */

     for (argc--,argv++; argc > Ø; argc--,argv++){
          printf("\n%s\n",*argv);
          printf(
           "Seconds Periods #shifts sfc(g/kw-h) fuel(kg/h)\n");
          /* periods one to 15 data periods, min or sec      */
          for (period = Ø; period < 15; ++period){
               /* file is opened and closed in this loop     */
               /* because the fseek function was not         */
               /* repositioning to the beginning of file     */
               /* For better programming, this should be     */
               /* outside loop and fseek(lptr,ØL,Ø) here     */
               if ((lptr=fopen(*argv,"r"))==NULL){
                    fprintf(stderr,"gear: cannot open %s\n",
                         *argv);
                    exit(1);
               }
               d = mdata;     /* set ptr to data struct      */
               savings[Ø].sfcct = Ø;    /* zero values in    */
               savings[Ø].shift = Ø;    /* threshold struct */
               savings[Ø].sfcsum = Ø.;
               savings[Ø].gear = Ø.;
               savings[Ø].fuel = Ø.;
               /* loop gets next set of data with period+1   */
               /* time periods, which are avg for analysis   */
               while (fillrec(d,period +1) > NULL){
                    if (tavg(period+1,d,avgd) < Ø){
                         continue; /* data varies, try next */
                    }
                    updat = upshift;         /* set ptr     */
                    upgrratio = LOW_GR_R;    /* set grratio */
                    data_calc(avgd->thz,avgd->kw,
                                        upgrratio,updat);
                    do{  /* fill in ratios with gearup       */
                         ++updat;  /* incr ptr in struct     */
                         gearup(avgd->thz,avgd->kw,
                                        upgrratio,updat);
```

```
                          upgrratio = updat->tr;
                     }while (upgrratio > avgd->tr);
                     copydata(avgd,updat);    /* current gr  */
                     nowd = updat;  /* mark place with ptr   */
                     upgrratio = avgd->tr;
                     shifts = -1;   /* init, is pre-incr     */
                     do{  /* add gear ups to minimum rpm     */
                          updat++;  /* incr ptr to struct    */
                          shifts++; /* incr for # gearups    */
                          num= gearup(avgd->thz,avgd->kw,
                                              upgrratio,updat);
                          upgrratio = updat->tr;
                     }while (num == 0);
                     /* call sub to analyze data in upshift  */
                     if (num != 4){
                          avg_th(nowd,shifts,
                               BASE_TIME * (period + 1),savings);
                     }
                }
                printavg(BASE_TIME*(period+1),savings);
                fclose(lptr);  /* in loop, fseek not working */
           }
      }
}

/*
 * subroutine to fill the array of data points for the
 * number of periods for current averaged time period
 * length of interest.
 */
fillrec(dptr,num)
register struct data *dptr;
register int   num;
{
     register int i;
     for (i=0; i < num; i++){
          if (nxrec(dptr) <= 0)    /* watch for end of file */
               return(EOF);
          dptr++;
     }
     return(num);
}

/*
 * Subroutine to determine which gear should be
 * used according to the decision algorithm
 * for the input data and time period.
 * Result of anal stored in a thold structure.
 */

avg_th(userd,shifts,time,thp)
struct data *userd; /* ptr to upshift array to in data gear */
int shifts;    /* number of gears above current in upshift  */
```

```
int time;       /* number of seconds in time period             */
        /* ptr to structure thold to speed access               */
register struct thold *thp;
{
        /* ptrs to structure data to speed access               */
    register struct data *grupd,*nowd;
    struct data nowdd;  /* working data structure for sub   */
    nowd = &nowdd; /* set ptr to working structure           */
    if (thp->gear < GEAR_TOL){     /* First pass init gear  */
        thp->gear = userd->tr;   /* ratio in thold struct */
    }

    /* checks for differing time periods same as thold.c    */
    /* no check next lower gear for use instead of optimum */
    /* uses defined rpm and rack limits from engine.h        */
    grupd = choose_gear(userd,LIMIT_LOW_RPM,
                                        LIMIT_HI_RACK,shifts);
    data_calc(userd->thz,userd->kw,thp->gear,nowd);
    if (nowd->rpm > FULL_RPM){
                /* check that engine speed is in range   */
                /* assume operator had shifted to gear   */
                /* that gave the ground speed using      */
                /* highest engine rpm, set the grupd     */
                /* to highest data with rpm < FULL RPM   */
        grupd = userd;
        while (grupd->rpm < FULL_RPM){
            grupd--;
            if (grupd <= upshift)
                break;
        }
        grupd++;  /* to point at data just below FULL RPM */
        fuelstat(thp,grupd,time);
        shiftstat(thp,grupd);
    }
    else if (nowd->rpm < LIMIT_LOW_RPM ||
            nowd->rack > (LIMIT_HI_RACK * maxrk(nowd->rpm))) {
                /* gear to high, must shift down         */
        fuelstat(thp,grupd,time);
        shiftstat(thp,grupd);
    }
    else if ((nowd->ff - grupd->ff) > LIMIT_FUEL_SAV){
                /* potential savings, shift              */
                /* past period in nowd for fuel stat     */
        fuelstat(thp,nowd,time);
        shiftstat(thp,grupd);
    }
    else{
                /* else not forced to shift, up or down */
        fuelstat(thp,nowd,time);
    }
}

/* routine for printing to stdout the results
```

```
 * from changing the length of time averaged
 * for basing decisions upon.
 */

printavg(time,th)
register int   time;
register struct thold *th;
{
     printf("%3d",time);
     printf("  %4d", th->sfcct);
     printf("  %3d", th->shift);
     printf("  %.2f", (th->sfcsum / th->sfcct));
     printf("  %.2f\n", (th->fuel/(th->sfcct*time/3600.)));
}
```

```
#include "engine.h"
#include "gear.h"
#include "tr.h"

/* routine to determine results from shifting up one gear
 * from current (passed tratio).  results put in structure
 * pointed to by ptr updata.  Following returned
 *    0) none of the following occur.
 *    1) engine speed drops below low rpm limit
 *    2) rack becomes greater than high rack limit
 *    3) gear up is a road gear, i.e. defined road gear
 *    4) tratio out of table range (too large)
 */

gearup(thz,power,tratio,updata)
float     thz;       /* trans. hertz for ground speed   */
float power,tratio; /* kilowatts, current gear ratio   */
register struct data *updata; /* where to put result   */
{
     register int i;
          /* loop thru gear table, find next higher    */
     for (i=0; tratio < (gratio[i] + GEAR_TOL); ){
          if ( ++i>= NO_GEARS)
               return(4);
     }
          /* call sub to fill data for the gear ratio  */
     data_calc(thz,power,gratio[i],updata);
          /* return value depends on results in updata */
     if (updata->rpm < LIMIT_LOW_RPM)
          return(1);
     if (updata->rack > LIMIT_HI_RACK*maxrk(updata->rpm))
          return(2);
     if (updata->tr < (gratio[ROAD_GR] + GEAR_TOL))
          return(3);
     return(0);
}

/* subroutine to actually fill in data structure pointed
 * at by dptr, assumes incoming information is valid
 */

data_calc(thz,power,tratio,dptr)
float     thz;       /* trans. hertz for ground speed   */
float power,tratio; /* kilowatts, current gear ratio   */
register struct data *dptr;   /* where to put result   */
{
     dptr->thz = thz;
     dptr->ehz = tratio * thz;
     dptr->tr = tratio;
     dptr->rpm = ehz_rpm(dptr->ehz);     /* pulse/sec to rpm */
     dptr->rack = rkhat(dptr->rpm,power);
     dptr->kph = thz_kph(thz);                    /* thz to kph  */
     dptr->kw = power;
```

```
     dptr->ff = fflow(dptr->rpm,dptr->rack);
     dptr->sfc = dptr->ff / power *1000.; /*kg/kWh to g/kWh */
}

/*following routine determines if the passed value is a
 * gear ratio within set tolerance. If it is found in the
 * gratio table it position is returned, or 0 thru NO_GEARS.
 * If not found a -1 is returned.
 * gears checked to within tolerance set in engine.h
 */
is_gear(ratio)
float ratio;
{
     register int i;
     for (i=0; ratio < (gratio[i] - GEAR_TOL); )
          if ( ++i>= NO_GEARS)
               return(-1);
     if ( ratio < (gratio[i] + GEAR_TOL))
          return(i);
     return(-1);
}
```

```
/* copy contents of one data structure to second  */
#include "gear.h"

copydata(from,to)
register struct data *from,*to;
{
     to->thz = from->thz;
     to->ehz = from->ehz;
     to->tr  = from->tr;
     to->rpm = from->rpm;
     to->rack= from->rack;
     to->kph = from->kph;
     to->kw  = from->kw;
     to->ff  = from->ff;
     to->sfc = from->sfc;
}
```

```
/* function that returns the predicted power in kW
 * for the passed rack and engine rpm.
 * Equations same as reported in MCR84-105 paper.
 */
double
kW(rpm,rack)
float rpm;
float rack;
{
     return(-84.1523 + 0.0640580*rpm + 0.2172268*rack
          -0.0000310556*rpm*rpm + 0.0005306494*rpm*rack);
}

/*
 * function that returns estimated fuel flow in kg/hr
 * given a rack and engine rpm.
 */
double
fflow(rpm,rack)
float rpm;
float rack;
{
     return(-4.3218 + 0.0047590*rpm - 0.0503982*rack
          -0.0000019147*rpm*rpm + 0.0006615262*rack*rack
          + 0.0000768939*rpm*rack);
}

/*
 * function to return the predicted rack given a power in kW
 * and an engine rpm.
 */
double
rkhat(rpm,power)
float rpm;
float power;
{
     return(124.7008 - 0.0827113*rpm + 1.4695318*power
          +0.0000256426*rpm*rpm - 0.0003370157*rpm*power);
}

/*
 * returns maximum rack value for passed rpm,
 * egn from regression of 100% torque data points.
 */
double
maxrk(rpm)
register float rpm;
{
     /* original logic in gear selection aid used rack set
      * above 140 to look for power overload.  The following
      * is to use 140 as 95% rack. Used by compiling with -DR140
      */
#ifdef R140
```

```
     return(140./0.95);
#else
     /*
      * Following is equation used to find maximum rack for
      * given speed. Should prevent overload.  Program is to
      * mult by desired fraction, ie .95 for 95%
      */
     return(0.1885553*rpm - 0.0000461812*rpm*rpm - 40.7732);
#endif
}

/*
 * converts engine hertz input to engine rpm and returns result.
 */
double
ehz_rpm(hertz)
float hertz;
{
     return(hertz * 60./132.);     /* pulse/sec to rpm */
}

/*
 * converts output hertz from transmission
 * to ground speed in kph
 */
double
thz_kph(thz)
float thz;
{
          /* thz to mph to kph     */
     return( thz * 0.014615 * 1.609344);
}
```

```
#include "gear.h"

/* subroutine to read next data record to drive simulation  */
/* this routine set to read in one minute averaged data     */

nxrec(d)
register struct data *d;
{
     register int ret;
     ret = fscanf(lptr,
          "%2d%2d%2d%2d%2d %f %f %f %f %f %f %f %f %f\n",
          &yr,&mo,&dy,&hr,&min,
          &d->thz,&d->ehz,&d->tr,&d->rack,&d->rpm,
          &d->kph,&d->kw,&d->ff,&d->sfc);
     if (ret == EOF) return(EOF);
     if (ret < 14) return(NULL);
     return(ret);
}
```

```
#include "gear.h"

/* subroutine to read next data record to drive simulation  */
/* version of nxrec for reading four second data            */

nxrec(d)
register struct data *d;
{
     register int ret;
     ret = fscanf(lptr,"Y%2d%2d%2d%2d%2d\n",
                              &yr,&mo,&dy,&hr,&min);
          /* if no Y for date, proceeding does nothing */
     if (ret == EOF) return(EOF);
     ret = fscanf(lptr,"%f %f %f %f %f %f %f %f %f\n",
          &d->thz,&d->ehz,&d->tr,&d->rack,&d->rpm,
          &d->kph,&d->kw,&d->ff,&d->sfc);
     if (ret == EOF) return(EOF);
     if (ret < 9) return(NULL);
     return(9);
}
```

```
#include "engine.h"
#include "gear.h"

/* averages data in structure at dptr and
 * places result in data struct pointed at by avg
 */

tavg(period,dptr,avg)
register int period;     /* number of periods to be avg     */
register struct data *avg,*dptr;
{
     register int i;
     int  send;
     send = Ø;       /* return Ø if no shift in avged data   */
     avg->thz = Ø.;
     avg->rack = Ø.;
     avg->tr  = Ø.;
     for (i=Ø;i<period;i++){
               /* avg data needed to find kW and thz to     */
               /* call data_calc, which will fill in rest   */
          avg->thz += dptr->thz/period;
          avg->tr  += dptr->tr/period;
          avg->rack += dptr->rack/period;
               /* tell caller if data outside limits        */
          if ((dptr->kph < LOW_SPEED) || (TOP_SPEED < dptr->kph))
               send = -1;
          if ((dptr->kw < LOW_POW) || (dptr->kw > HI_POW))
               send = -1;
          dptr++;
     }
     avg->kw = kW(ehz_rpm(avg->thz*avg->tr), avg->rack);
     data_calc(avg->thz,avg->kw,avg->tr,avg);
     return(send);
}
```

```
#include "engine.h"
#include "thold.h"

/* initialize the thresh hold data structures       */
initth()
{
     subinit(&savings[0],      MIN_SAV, MAX_SAV, INC_SAV);
     subinit(&rack[0],         MIN_RACK, MAX_RACK, INC_RACK);
     subinit(&engrpm[0],       MIN_RPM, MAX_RPM, INC_RPM);
     subinit(&lastgr[0],       MIN_LGR, MAX_LGR, INC_LGR);
     subinit(&sumloss[0],      MIN_SUM, MAX_SUM, INC_SUM);

     operator.shift  = fullrpm.shift  = 0;
     operator.sfcsum = fullrpm.sfcsum = 0.;
     operator.sfcct  = fullrpm.sfcct  = 0;
     operator.gear   = fullrpm.gear   = 0.;
     operator.fuel   = fullrpm.fuel   = 0.;
}

subinit(th,min,max,incr)
register struct thold *th;
float min,max,incr;
{
     register float z;

     for (z=min; z<max; z+= incr){
          th->value = z;
          th->shift = 0;
          th->sfcsum =0.;
          th->sfcct = 0;
          th->gear  = 0.;
          th->fuel  = 0.;
          ++th;
     }
     /* set last value above MAX, used to stop loops    */
     th->value = z;
}
```

```
#include "engine.h"
#include "gear.h"
#include "thold.h"

/* subroutine to analyze the recommendations by the
 * gear selection aid as the threshold parameters
 * are varied.
 */

thold(userd,shifts,time)
struct data *userd; /* ptr to operator data in upshift */
int shifts;         /* possible gears above userd      */
int time;           /* number of seconds in time       */
{
     register struct data *grupd,*nowd;
               /* ptrs to data structures for faster access */
     struct data *maxd;  /*ptr to lowest gear, rpm<FULL RPM */
     struct data nowdd;  /* working data structure          */
     register struct thold *thp;   /* ptr to thold struct   */
     register int i;     /* fast counter for loops          */
     int  maxgr_is,nowgr_is,upgr_is; /* gears in gratio[]   */
     float     (*fflp)[NO_GEARS];  /* ffloss 2-d array ptr  */
          /* () required to make a ptr to arrays of NO_GEAR */
     nowd = &nowdd; /* set ptr to work structure            */
          /*set ptr to upshift data, highest rpm < FULL RPM */
     maxd = userd;
     while (maxd->rpm < FULL_RPM){
          maxd--;
          if (maxd <= upshift)
               break;
     }
     maxd++;   /* to point at data just below FULL RPM      */
     /* First pass init gear ratios in thold struct arrays  */
     /* uses operator gear as starting point for analysis   */
     if (savings[Ø].gear < GEAR_TOL) {
          for (thp = savings; thp->value <= MAX_SAV; thp++){
               thp->gear = userd->tr;
          }
          for (thp = rack; thp->value <= MAX_RACK; thp++){
               thp->gear = userd->tr;
          }
          for (thp = engrpm; thp->value <= MAX_RPM; thp++){
               thp->gear = userd->tr;
          }
          for (thp = lastgr; thp->value <= MAX_LGR; thp++){
               thp->gear = userd->tr;
          }
          for (thp = sumloss; thp->value <= MAX_SUM; thp++){
               thp->gear = userd->tr;
          }
     }
     /* threshold fuel savings kg/hr as defined in thold.h  */
     /* checks if shifting reduces fuel use more than thres */
```

```
     /* no check of lower gear for use instead of optimum    */
     /* uses defined rpm and rack limits in engine.h         */

     /* find grupd, highest gear within engine operation     */
     grupd = choose_gear(userd,LIMIT_LOW_RPM,
                                   LIMIT_HI_RACK,shifts);
     /* loop and check for each threshold value              */
     for (thp = savings; thp->value <= MAX_SAV; thp++){
          /* fill working data structure using gear ratio    */
          /* chosen in previous call (time period) to sub    */
          data_calc(userd->thz,userd->kw,thp->gear,nowd);
          if (nowd->rpm > FULL_RPM){
               /*check that engine speed is in range */
               /* must shift up for ground speed  */
               fuelstat(thp,maxd,time);
               shiftstat(thp,maxd);
          }
          else if (nowd->rpm < LIMIT_LOW_RPM ||
               nowd->rack > (LIMIT_HI_RACK * maxrk(nowd->rpm))) {
               /* current gear to high, must shift down      */
               fuelstat(thp,grupd,time);
               shiftstat(thp,grupd);
          }
          else if ((nowd->ff - grupd->ff) > thp->value){
               /* potential fuel savings, shift up           */
               /* past period in nowd for fuel stat          */
               fuelstat(thp,nowd,time);
               shiftstat(thp,grupd);
          }
          else{
               /* else not enough savings to shift,          */
               /* and not forced to shift down               */
               fuelstat(thp,nowd,time);
          }
     }
          /* analysis of alternate decision basis.     */
     /* fuel savings based on running sum of lost potential */
     /* fuel savings incrementally between gears            */
     /* no check of lower gear for use instead of optimum   */
     /* uses 1500rpm and 95% rack lower limits              */
/*   grupd = choose_gear(userd,LIMIT_LOW_RPM,
     /*                            LIMIT_HI_RACK,shifts);
     /* grupd still set from above                          */
     /* find position in gear table for various data sets   */
     /* within upshift, later used to set incremental       */
     /* savings in the ffloss array, max is highest rpm     */
     if ((maxgr_is = is_gear(maxd->tr)) < 0){
               /* may be operator gear, not always in toler */
          if ((maxgr_is = is_gear(maxd[-1].tr)) < 0){
               fprintf(stderr,
               "cannot find gear:%2d%2d%2d%2d%2d\n",
               yr,mo,dy,hr,min);
          }
```

```
    }
    /* upgr for highest gear still in rpm and rack limits  */
    if ((upgr_is = is_gear(grupd->tr)) < 0){
                /* may be operator gear, not always in toler */
         if ((upgr_is = is_gear(grupd[-1].tr)) < 0){
              fprintf(stderr,
              "didnot find gear:%2d%2d%2d%2d%2d\n",
              yr,mo,dy,hr,min);
         }
    }
         /* do analysis for each threshold value              */
    for (thp = sumloss,fflp = ffloss;
                        thp->value <= MAX_SUM;thp++,++fflp){
         float     fuel_loss;
         int  fuel_lgr;
         if (thp->sfcct == 0){    /* 1st pass, init to 0   */
              for (i=0;i < NO_GEARS;i++)
                   (*fflp)[i] = 0.;
         }
         /* data for gear chosen prev time period     */
         /* uses gearup, sure gear is in the gear tbl */
         gearup(userd->thz,userd->kw,
                        (thp->gear + 2.*GEAR_TOL),nowd);
         add_loss(fflp,upshift,time);
         /* number gear and verifies in gear ratio table   */
         if ((nowgr_is = is_gear(nowd->tr)) < 0){
              fprintf(stderr,
              "unable find gear:%2d%2d%2d%2d%2d\n",
              yr,mo,dy,hr,min);
         }
         /* clear fuel loss in fflp from low gear below    */
         /* lowest usable gear and current gear (in maxgr  */
         /* and nowgr), and above highest usable gear      */
         /* (in grup) to top of gear table. Says no        */
         /* savings or the gear not usable                 */
         for (i = 0;i <= maxgr_is; i++)
              (*fflp)[i] = 0.;    /* zero lower gears      */
         for ( ;i <= nowgr_is; i++)
              (*fflp)[i] = 0.;    /* zero lower gears      */
         fuel_loss = (*fflp)[i];  /* i at next gear up     */
         fuel_lgr  = i; /* keep gear and incr saving       */
         /* note if upgr == nowgr, entire array cleared    */
         for (i = upgr_is + 1; i < NO_GEARS;i++)
              (*fflp)[i] = 0.;
         if (nowd->rpm > FULL_RPM){
              /* operator using faster speed, result is nowd
              /* has too high engine speed. So shift to rpm
              /* below FULL RPM and look for savings next
              /* time period. fflp already cleared properly.
               */
              fuelstat(thp,maxd,time);
              shiftstat(thp,maxd);
         }
```

```
        else if (nowd->rpm < LIMIT_LOW_RPM ||
             nowd->rack > (LIMIT_HI_RACK * maxrk(nowd->rpm))) {
                  /* gear to high, must shift down          */
             fuelstat(thp,grupd,time);
             shiftstat(thp,grupd);
             for (i = Ø;i <= NO_GEARS; i++)
                  (*fflp)[i] = Ø.;    /* zero all gears    */
        }
        else if (fuel_loss > thp->value){
             /* incr savings > threshold, where to shift? */
             /* This shifts up each gear that incr saving */
             /* > threshold, can easily change to shift   */
             /* only one gear up now to allow smoother    */
             /* shifting in some applications.            */
             register struct data *dd;
             (*fflp)[fuel_lgr] = Ø.;
             if ( (*fflp)[fuel_lgr + 1] > thp->value){
                  ++fuel_lgr;    /* next gr meets thresh   */
                  (*fflp)[fuel_lgr] = Ø.;
             }
             for (dd = upshift;
                       is_gear(dd->tr) < fuel_lgr; dd++);
             assert(dd < &upshift[2Ø]);
                  /* past period in nowd for fuel stat     */
             fuelstat(thp,nowd,time);
             shiftstat(thp,dd);
        }
        else{
             /* else not enough savings to shift,     */
             /* or not forced down                    */
             fuelstat(thp,nowd,time);
             /* fflp is already cleared               */
        }
   }
   /* Rack limit fraction of max rack at engine rpm         */
   /* no check of lower gear for use instead of optimum     */
   /* use defined limits for rpm and 'savings to shift'     */
   for (thp = rack; thp->value <= MAX_RACK; thp++){
        /* locate gear within rpm and rack limits           */
        grupd = choose_gear(userd,LIMIT_LOW_RPM,
                                  thp->value,shifts);
        /* calc data for gear chosen previous time per      */
        data_calc(userd->thz,userd->kw,thp->gear,nowd);
        if (nowd->rpm > FULL_RPM){
             /*check that engine speed is in range */
             fuelstat(thp,maxd,time);
             shiftstat(thp,maxd);
        }
        else if (nowd->rpm < LIMIT_LOW_RPM ||
             nowd->rack > (LIMIT_HI_RACK * maxrk(nowd->rpm))) {
             /* gear to high, must shift down   */
             fuelstat(thp,grupd,time);
             shiftstat(thp,grupd);
```

```
            }
            else if ((nowd->ff - grupd->ff) > LIMIT_FUEL_SAV){
                /* potential savings, shift                    */
                /* past period in nowd for fuel stat           */
                fuelstat(thp,nowd,time);
                shiftstat(thp,grupd);
            }
            else{
                /* else not enough savings to shift,           */
                /* or not forced down                          */
                fuelstat(thp,nowd,time);
            }
        }
        /* engine rpm threshhold analysis                      */
        /* no check of lower gear for use instead of optimum   */
        /* uses defined rack limit and 'savings to shift'      */
        for (thp = engrpm; thp->value <= MAX_RPM; thp++){
            /* find high gear in upshift meeting rack and rpm */
            grupd = choose_gear(userd,
                            thp->value,LIMIT_HI_RACK,shifts);
            /* calc data for gear chosen previous time per     */
            data_calc(userd->thz,userd->kw,thp->gear,nowd);
            if (nowd->rpm > FULL_RPM){
                /*check that engine speed is in range */
                fuelstat(thp,maxd,time);
                shiftstat(thp,maxd);
            }
            else if (nowd->rpm < LIMIT_LOW_RPM ||
                nowd->rack > (LIMIT_HI_RACK * maxrk(nowd->rpm))) {
                /* gear to high, must shift down   */
                fuelstat(thp,grupd,time);
                shiftstat(thp,grupd);
            }
            else if ((nowd->ff - grupd->ff) > LIMIT_FUEL_SAV){
                /* potential savings, shift                    */
                /* past period in nowd for fuel stat           */
                fuelstat(thp,nowd,time);
                shiftstat(thp,grupd);
            }
            else{
                /* else not enough savings to shift,           */
                /* or not forced down                          */
                fuelstat(thp,nowd,time);
            }
        }
        /* use next lower gear instead of optimum if loss */
        /* from optimum gear is LESS than the threshold   */
        /* uses defined limit rpm, 'savings to shift'     */
        /* and rack limit                                 */
        /* find grupd, highest gear within engine operation    */
        for (thp = lastgr; thp->value <= MAX_LGR; thp++){
            /* find grupd, high gear within engine operation  */
            grupd = choose_gear(userd,LIMIT_LOW_RPM,
```

```
                                        LIMIT_HI_RACK,shifts);
        /* check lower gear for loss from opt gear   */
        if ((grupd[-1].ff - grupd->ff) < thp->value)
            grupd--;
        data_calc(userd->thz,userd->kw,thp->gear,nowd);
        if (nowd->rpm > FULL_RPM){
            /*check that engine speed is in range */
            fuelstat(thp,maxd,time);
            shiftstat(thp,maxd);
        }
        else if (nowd->rpm < LIMIT_LOW_RPM ||
            nowd->rack > (LIMIT_HI_RACK * maxrk(nowd->rpm))) {
            /* gear to high, must shift down    */
            fuelstat(thp,grupd,time);
            shiftstat(thp,grupd);
        }
        else if ((nowd->ff - grupd->ff) > LIMIT_FUEL_SAV){
            /* potential savings, shift              */
            /* past period in nowd for fuel stat    */
            fuelstat(thp,nowd,time);
            shiftstat(thp,grupd);
        }
        else{
            /* else not enough savings to shift,            */
            /* or not forced down                           */
            fuelstat(thp,nowd,time);
        }
    }
    /* check actual operator performance    */
    if (((userd->tr - GEAR_TOL)>operator.gear) ||
       (operator.gear>(userd->tr+GEAR_TOL))){
        /* operator changed gear */
        shiftstat(&operator,userd);
    }
    fuelstat(&operator,userd,time);
    /* check performance at full engine speed    */
    /* for worst case fuel usage                 */
    /* to check other analysises against         */
    if (((maxd->tr - GEAR_TOL)>fullrpm.gear) ||
                (fullrpm.gear>(maxd->tr+GEAR_TOL))){
        /* change gear to stay at full rpm */
        shiftstat(&fullrpm,maxd);
    }
    fuelstat(&fullrpm,maxd,time);
}
```

```
#include "engine.h"
#include "gear.h"
#include "thold.h"

/* subroutine to do summing and counter
 * incrementing for fuel related info
 */

fuelstat(thp,dp,time)
register struct thold *thp;
register struct data  *dp;
int  time;
{
          /* add sfc to sum and increment counter */
          /* will be divided for average later    */
     thp->sfcsum += dp->sfc;
     thp->sfcct++;
          /* add fuel used in period to sum       */
          /* fuel = kg/hr * sec/(3600s/hr) = kg   */
     thp->fuel += dp->ff * time / 3600.;
}

/* subroutine to do assigning and counter
 * incrementing for shift related info
 */

shiftstat(thp,dp)
register struct thold *thp;
register struct data  *dp;
{
          /* save chosen gear this time period    */
          /* so next time period will know        */
     thp->gear = dp->tr;
          /* count number of shifts               */
     thp->shift++;
}

/* choose gear from upshift that meets
 * minimum rpm and max rack settings
 * returns pointer into upshift to data
 * return will also be lowest sfc in limits
 */

struct data *
choose_gear(userd,rpm,rack,shifts)

struct data *userd; /* pointer to operating point */
float     rpm,rack; /* limits on rack and rpm     */
int  shifts;        /* number gears above userd   */
{
     register struct data *grd,*lowsfc;
     register int   i;
     grd = lowsfc = userd;
```

```
     for (i = 0; i < shifts; i++){
          /* move pointer to highest gear in upshift   */
          ++grd;
          /* check that sfc is decreasing              */
          if (grd->sfc < lowsfc->sfc)
               lowsfc = grd;
     }
     /* bring ptr back into low engine rpm limit       */
     while (lowsfc->rpm < rpm){
          --lowsfc;
          assert(lowsfc >= upshift);
     }
     /* bring ptr back till rack below rack limit, or  */
     /* to highest rpm if rack limit cannot be met     */
     while (lowsfc->rack > (rack * maxrk(lowsfc->rpm))){
          lowsfc--;
          if ((lowsfc->tr >= LOW_GR_R) ||
                                   (lowsfc->rpm > FULL_RPM)){
               /*assume insufficient power, use gear with   */
               /*highest engine rpm < FULL RPM              */
               lowsfc++;
               break;
          }
     }
     /* assertions to check that values are reasonable */
     assert(lowsfc >= upshift);
     assert(lowsfc <= &upshift[20]);
     assert(HI_GR_R < lowsfc->tr);
     assert(LOW_GR_R > lowsfc->tr);
     assert(lowsfc->rpm <= FULL_RPM);
     return(lowsfc);
}

/* find incremental shift loss by not
 * shifting up to next gear higher and
 * add incr fuel loss to array of losses.
 */
add_loss(lossp,upd,time)
register float *lossp;   /* ptr to ffloss array, allows     */
               /* this sub to see as a 1-dimensional array  */
register struct data *upd;    /* ptr to bottom of upshift   */
int  time;     /* time in seconds  */
{
     register int i;
     float lastff;
     lastff = upd->ff;
     for (upd++; upd->tr > HI_GR_R; upd++){
          if ((i= is_gear(upd->tr)) >= 0){
               lossp[i] += (lastff - upd->ff) * time/3600.;
               lastff = upd->ff;
          }
     }
}
```

```
#include "engine.h"
#include "gear.h"
#include "thold.h"

/* output to stdout the thresh hold data structures    */
printth(time)
register int   time;     /* no. of seconds in period   */
{
     printf("\nOPERATOR PERFORMANCE\n");
     printf("#shift #periods sfc(g/kw-h) fuel(kg/h)\n");
     printf("%3d\t%3d\t%.3f\t\t%.3f\n",operator.shift,
          operator.sfcct,(operator.sfcsum/operator.sfcct),
          (operator.fuel/(operator.sfcct*time/3600.)));
     printf("\nFULL ENGINE SPEED WORST CASE\n");
     printf("#shift #periods sfc(g/kw-h) fuel(kg)/h\n");
     printf("%3d\t%3d\t%.3f\t\t%.3f\n",fullrpm.shift,
          fullrpm.sfcct,(fullrpm.sfcsum/fullrpm.sfcct),
          (fullrpm.fuel/(fullrpm.sfcct*time/3600.)));
     printf("\nSAVINGS\n");
     printf("Value #shifts sfc(g/kw-h) fuel(kg/h)\n");
     subprint(savings, MAX_SAV,time);
     printf("\nRACK\n");
     subprint(rack, MAX_RACK,time);
     printf("\nENGINE RPM\n");
     subprint(engrpm, MAX_RPM,time);
     printf("\nLOWER GEAR FOR POWER\n");
     subprint(lastgr, MAX_LGR,time);
     printf("\nACCUMULATED LOST POTENTIAL SAVINGS\n");
     subprint(sumloss, MAX_SUM,time);
}

/* easier to put looping in separate sub     */
subprint(th,max,time)
register struct thold *th;
float max;
register int   time;
{
     for (; th->value < max; th++){
          assert(operator.sfcct == th->sfcct);
          printf("%.2f\t%3d\t%.2f\t%.2f\n",
               th->value,th->shift,
               (th->sfcsum / th->sfcct),
               (th->fuel/(th->sfcct*time/3600.)));
     }
}
```

```
#include "stdio.h"
#include "gear.h"
#include "thold.h"

/* print routines for data structures data and thold.
 * intended mainly for debugging of programs.
 * output is to stderr.
 */

databug(dptr)
register struct data *dptr;
{
     fprintf(stderr,"%02d%02d%02d%02d%02d\t",yr,mo,dy,hr,min);
     fprintf(stderr,"thz=%.1f\tehz=%.1f\ttr=%.3f\track=%.1f\n",
          dptr->thz,dptr->ehz,dptr->tr,dptr->rack);
     fprintf(stderr,
          "kph=%.1f\trpm=%.1f\tkw=%.1f\tff=%.2f\tsfc=%.2f\n",
          dptr->kph,dptr->rpm,dptr->kw,dptr->ff,dptr->sfc);
}


thbug(tptr)
register struct thold *tptr;
{
     fprintf(stderr,"val=%.2f\tshift=%3d\tgear=%.3f\n",
          tptr->value,tptr->shift,tptr->gear);
     fprintf(stderr,"sfcsum=%.1f\tsfcct=%3d\tfuel=%.3f\n",
          tptr->sfcsum,tptr->sfcct,tptr->fuel);
}
```

EVALUATION OF A GEAR SELECTION AID
FOR FUEL EFFICIENT TRACTOR OPERATION

by

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ABSTRACT

This research evaluated and analyzed the decision algorithm of a tractor gear selection aid. The gear selection aid developed for an International Harvester model 3588 four wheel drive tractor used inputs of engine speed, engine rack position (injection pump plunger sleeve pin position), and transmission output speed. A SYM-1 microcomputer used mathematical models to relate these inputs to current fuel consumption and power. If the tractor could be operated more economically in a higher gear with a reduced throttle setting, the gear selection aid made a shift up and throttle back recommendation to the operator.

New mathematical models were developed for the SYM-1 program that included a larger portion of the engine performance range. The tractor was then placed with operators to determine their acceptance of the gear selection aid in actual field conditions. Operators first used the tractor with the display switched off to determine their normal settings and load patterns. With the display switch on the fuel savings attributed to the gear selection aid ranged from no savings to 25.7% during this research. Including the operators who used the tractor prior to this research, ten operators averaged a 12.5% reduction in fuel consumption with the gear selection aid.

A simulation program was developed to determine the validity of the parameter limits used in the gear selection aid program. The simulation varied the lower engine speed limit, maximum rack

position limit, minimum threshold fuel savings to recommend a shift, maximum fuel loss to consider the next higher gear than the optimum, and time period length over which the data was averaged. The program also considered an alternate decision algorithm that integrated the incremental fuel loss between gears over time and recommended a shift when a minimum threshold was met. The program determined the fuel consumption and shift frequency to maintain the optimum conditions within the varied parameter limits.

Increasing the averaging time period caused the predicted specific fuel consumption to decrease. The specific fuel consumption is nonlinear over the engine performance map. Averaging loads over longer periods resulted in a lower specific fuel consumption than the average specific fuel consumption of lower and higher loads for shorter time periods.

The shift frequency increased and the specific fuel consumption decreased by raising the fuel threshold limits, raising the rack limit and lowering the low engine speed limit. Changing the limits in the reverse direction caused the opposite results. The algorithm integrating fuel loss between gears had consistently near or had the lowest specific fuel consumption at a shift frequency. The simulation program summary showed that the ten operators averaged over 11 shifts per hour, even higher than the predicted shift frequency from following all gear selection aid recommendations.